Posidonia oceanica banquettes removal: sedimentological, geomorphological and ecological implications.

PhD Thesis

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Alla mia Famiglia
e a Gioia

Contents

Abstract

The beach cast leaf litter of the seagrass *Posidonia oceanica* are commonly found along the Mediterranean coasts. In the sandy shores cast litter form a wedge structures from few centimeters to several meters thick, defined 'banquettes' which are currently removed in order to favor the beach exploitation for tourist activities overall Mediterranean region.

This study aims to investigate the role of *Posidonia oceanica* seagrass beach cast litter deposition on the functioning of coastal systems, in order to evaluate the impact of banquettes removal operations.

The study was carried out following four specific aims analyzed and discussed in the chapters of the thesis:

I. to quantify the removed amounts of *P. oceanica* banquettes, as well as the related management practices (i.e., frequency and techniques of removal, dumping) in the island of Sardinia.
II. to investigate the deposition dynamics and the sediment trapping in the banquettes in beaches with different wave energy conditions.
III. to analyze the relationships between banquettes deposition and beach geomorphology within beaches characterized by different wave energy conditions.
IV. to quantify the nutrient loss for the meadows and the other coastal ecosystems, following the removal of banquettes.

Chapter2. Ongoing removal practices of *P. oceanica* banquettes were analyzed on Sardinia island in order to quantify this phenomenon on a broad scale and to evaluate the potential environmental impacts of banquettes removal and dumping on the coastal zone. This study were conducted along all the coastal area of Sardinia island for 116 beach (289 km total length). Total removed amount was estimated as 106,180 m^3, heavy machines were generally used to remove banquettes, in several beaches frequency of removal was monthly during the summer period. Furthermore the majority (80%) of the volume removed was dumped in non-authorized areas. Following the findings of the study, some management measures are suggested in order to minimize environmental impact of banquettes removal.

Chapter 3. This study investigates the deposition dynamics and sediments trapped in the banquettes on three beaches on the western coast of Sardinia (western Mediterranean) characterized by different wave energy conditions. Field measurements of banquettes volume were calculated using a Real Time Kinematic Differential Global Positioning System. Banquettes sampling was carried out in two different periods of the year, before and after the fall of *P. oceanica* leaves, and at two levels of the beach profile (i.e. foreshore and backshore). The sampling was aimed at analyzing rhizome biomass and sediment concentrations. The high energy beaches showed higher mean volumes of banquettes deposited during the year. Banquettes deposition occurs during the final phases of a storm event, when wave energy decreases. The landward limit of banquettes marks the maximum wave run-up, where heavier materials are deposited leading to higher sediment concentrations on the backshore. The sediment concentration in the banquettes was always higher on the backshore than on the foreshore and is independent from wave energy. Based on the findings of this study, the impact of banquettes removal on the sedimentary budget of Mediterranean beaches was discussed.

Chapter 4. This study investigates the variability of the morphology of same beaches during one year. The beaches are located in the western coast of Sardinia The beaches were mapped using 6 Real Time Kinematic Global Positioning System surveys. The results of this study highlight that in high energy beaches the deposition dynamics of banquettes is strictly correlated to the beach dynamics. Banquettes concurs with sediment to the morphological changes driven by beach dynamics process and contribute to the berm formation.

In the low energy beach banquettes are deposited as a layer over a generally invariant sedimentary substrate and vegetation litter deposits itself concur to the beach geomorphology. Banquettes removal from high energy beaches could significantly alter the processes which controls beach geomorphology, while the low energy beach is probably less sensitive to this kind of impact.

Chapter 5. The removal of banquettes was analyzed on the island of Sardinia in order to quantify the ecological implication for coastal ecosystem. The loss of biomass and the loss of nutritive element was assessed in 5 localities which collectively account for about 70% of *P. oceanica* removed from Sardinian beaches. The result obtained from this study highlight that the loss of biomass due to the removal varied between 1.8 and 14.9% of meadow production, and the loss of nutritive elements : N and P , is lesser than 6% of the meadow requirement.

Chapter 6. This chapter summarizes the remarks of the previous studies and the impact of banquettes removal on coastal geomorphology and coastal ecosystems as well as the impact due to the dumping of the material. Possible mitigation measure as well as further needed studies have been suggested.

Riassunto:

La lettiera della fanerogama marina spiaggiata di *Posidonia oceanica* si ritrova frequentemente in molte aree costiere del Mediterraneo. Lungo le coste sabbiose la lettiera forma degli estesi e spessi accumuli denominati ‘banquettes’ che sono frequentemente rimossi per favorire l’attività turistica. Scopo di questa tesi è studiare il ruolo della *Posidonia oceanica* spiaggiata sul funzionamento del sistema costiero, al fine di valutare gli impatti derivanti dalle operazioni di rimozione delle banquettes.

Lo studio è stato realizzato seguendo quattro specifici obiettivi analizzati e discussi nei capitoli che compongono la tesi di dottorato:

I. quantificare il volume di banquettes rimossi, le modalità di rimozione, la frequenza della rimozione e lo smaltimento del materiale rimosso lungo le coste della Regione Sardegna (Mediterraneo occidentale),

II. analizzare la dinamica deposizionale e la capacità di intrappolamento del sedimento nelle banquettes in spiagge a differente energia del moto ondoso,

III. analizzare le relazioni fra la deposizione delle banquettes e la geomorfologia delle spiagge in funzione dell’energia del moto ondoso,

IV. quantificare la perdita di elementi nutritivi per l’ecosistema costiero a seguito delle operazioni di rimozione delle banquettes.

Capitolo 2. Le modalità di rimozione delle banquettes nella Regione Sardegna sono state analizzate al fine di quantificare tale fenomeno a scala Regionale e valutare gli impatti potenziali della rimozione e dello smaltimento del materiale rimosso sulla fascia costiera. Lo studio ha interessato tutta la fascia costiera della Sardegna per un totale di 116 spiagge (289 Km di costa sabbiosa). Il volume di banquettes rimossi è stato stimato in 106,180 m^3, la rimozione viene effettuata con mezzi pesanti e in taluni casi con frequenza mensile durante il periodo estivo.

Il materiale rimosso viene smaltito per ca 80% in discariche non autorizzate. I risultati ottenuti hanno permesso di evidenziare gli impatti potenziali sulla fascia costiera, e suggerire alcune misure di mitigazione.

Capitolo 3. E’ stata analizzata la dinamica deposizionale e la capacità d’intrappolamento di sedimento nelle banquettes in spiagge caratterizzate da differente energia del moto ondoso localizzate nel settore occidentale della Sardegna. Il volume delle banquettes è stato misurato utilizzando un Differential Global Positioning System. Il campionameto delle banquettes è stato eseguito in due differenti periodi dell'anno (prima e dopo la perdita delle foglie da parte della *Posidonia oceanica*) e in due livelli lungo il profilo di spiaggia (battigia – retrospiaggia), al fine di misurare concentrazione di sedimento nelle banquettes. Nelle spiagge ad elevata energia il volume medio di banquettes deposto nel corso di un anno è maggiore che nella spiaggia a bassa energia. La deposizione delle banquettes ha luogo nelle fasi finali degli eventi di tempesta al decrescere dell'energia delle onde. Il margine delle banquettes verso terra coincide con il valore massimo del run-up dove vengono deposti i materiali più pesanti. Di conseguenza la concentrazione dei sedimenti nelle banquette è più alta nel retrospiaggia rispetto alla battigia. La concentrazione di sabbia nelle banquettes è indipendente dal livello di energia della spiaggia. Sulla base di questi risultati sono è stato valutato l'impatto della rimozione delle banquettes sul bilancio sedimentario delle spiagge.

Capitolo 4. Questo capitolo analizza la variabilità morfologica delle stesse spiagge nel corso di un anno. Le spiagge sono localizzate nella costa occidentale della Sardegna.

La morfologia delle spiagge è stata misurata utilizzando un Real Time Kinematic Differential Global Positioning System per 6 volte nell'arco dell'anno. Dai risultati dello studio è emerso che nelle spiagge ad elevata energia la deposizione delle banquettes è strettamente in relazione con la dinamica delle spiagge. Le banquettes concorrono, insieme al sedimento, ai cambiamenti morfologici della spiaggia e contribuiscono alla formazione della berma. Nelle spiagge a bassa energia le banquettes si depositano sul substrato sedimentario che non mostra variazioni morfologiche significative. La deposizione della lettiera determina le principali variazioni morfologiche. La rimozione delle banquettes dalle spiagge ad elevata energia può portare ad un alterazione dei processi che controllano la geomorfologia della spiaggia, mentre le spiagge a bassa energia sono meno sensibili a questo tipo di impatto.

Capitolo 5. La rimozione delle banquettes è stata analizzata al fine di valutare le implicazioni ecologiche sugli ecosistemi costieri. Si è valutata la perdita di biomassa e di elementi nutritivi a seguito delle operazioni di rimozione delle banquettes in 5 siti da cui in totale viene prelevato ca il 70 % del materiale rimosso in tutta la Sardegna. La perdita di biomassa a seguito della rimozione varia tra 1.8% e il 14.9 % rispetto alle adiacenti praterie di *Posidonia oceanica*, mentre la perdita di elementi nutritivi (N e P), è generalmente inferiore al 6% della richiesta di elementi nutritivi da parte delle praterie.

Capitolo 6. Tale capitolo riassume le principali conclusioni dei diversi studi e sintetizza sia gli impatti della rimozione delle banquettes sulla geomorfologia costiera, sull'ecosistema costiero e gli impatti dovuti alle operazioni di smaltimento Si suggeriscono inoltre alcune misure di mitigazione i i settori per i quali è necessario approfondire gli studi.

CHAPTER 1

Introduction, current state of art, aim of the study

1.1 Introduction

The beach cast leaf litter of the seagrass *Posidonia oceanica* are commonly found along the Mediterranean coasts. In the sandy shores cast litter form a wedge structures from few centimeters to several meters thick, defined “banquettes” by French authors (Jeudy de Grissac and Audoly, 1985; Boudouresque and Meisnesz, 1982), which are constituted by leaves, rhizomes and sediments (Jeudy de Grissac, 1984). *P. oceanica* banquettes are currently removed in order to favor the beach exploitation for tourist activities overall Mediterranean region (Duarte, 2004).

Despite banquettes have been often cited to have a role in the beach protection from erosion (Mateo et al., 2003, Boudouresque and Jeudy De Grissac, 1983) very few studies were published about this issue.

Banquettes could affect the beach geomorphology and could play a significant role in the beach morphodynamic, consequently their removal could have an impact on beach geomorphology. Furthermore the removal of litter can affect the functioning of coastal ecosystems following the permanent loss of nutritive elements fos coastal ecosystems.

1.2 Current state of art

*Interactions between seagrass meadows and coastal sedimentary processes**

*This Paragraph have been extracted from: De Falco, G., Baroli, M., Cucco, A., Simeone, S., 2008. Intrabasinal conditions promoting the development of a biogenic carbonate sedimentary facies associated with the seagrass *Posidonia oceanica*. Continental Shelf Research (in press).

Seagrass beds are highly productive coastal ecosystems having strong interactions with sedimentary processes (Madsen et al., 2001). Several studies have stressed the role of marine plants in modifying the hydrodynamics of the bottom boundary layer (Amos et al., 2004), in favoring fine sediment deposition and in buffering sediment re-suspension (Gambi et al., 1990; Fonseca, 1996; Komatsu, 1996; Gacia et al., 1999).

Seagrass epiphytes provide biogenic carbonate particles to the substrate, thus contributing to the production of mud-carbonate sediments. The production rate of biogenic carbonate from seagrass epiphytes has been quantified in the range 0.05 to 7.67 g m^{-2} day^{-1} (18 to 2,800 g m^{-2} $year^{-1}$) considering different seagrass species from tropical and temperate seas (Gacia et al., 2003 and reference therein). The development of mud-carbonate sediment facies associated with seagrass is related to latitude and local environmental conditions: the mud-carbonate production rate is generally higher in tropical than in subtropical and temperate areas, where seagrass sediments can be dominated by coarser siliciclastic particles (Perry and Beavington-Penney, 2005).

Posidonia oceanica is a marine phanerogam endemic to the Mediterranean basin which forms extended meadows along its coasts in a bathymetric range from the surface to 30-40 m depth in clear waters (Pergent et al., 1995).

Several studies have shown the influence and dependence of these meadows on the nature and dynamics of coastal sediments (Boudouresque and Jeudy de Grissac 1983; Jeudy de Grissac and Boudouresque 1985; Blanc and Jeudy de Grissac 1989). This plant is capable of adapting its growth rate and angle of its rhizome branches to the rate of sediment deposition (Boudouresque and Jeudy de Grissac 1983). In this way, *P. oceanica* creates a terraced structure (*matte*), consisting of an intertwining of roots, rhizomes and trapped sediments, which dampens the wave energy and affects the composition of the bottom sediments, buffering fine sediment re-suspension (Gacia et al., 1999) and enriching them in biogenic debris (Mateo et al., 1997).

The carbonate production from *P. oceanica* epiphytes is generally low (0.19 - 0.43 g m^{-2} day^{-1}, equivalent to 69 - 157 g m^{-2} $year^{-1}$) compared to other Mediterranean coastal benthic ecosystems (Canals and Ballesteros, 1997) or other tropical seagrasses (Gacia et al., 2003). However, the sediments collected inside the *P. oceanica* meadows in different Mediterranean sites showed high percentages of biogenic carbonate due to the fauna – e.g. gastropods, foraminifers, bivalves, echinoids, bryozoans - associated with the ecosystems (Jeudy de Grissac & Boudouresque 1985, Blanc and Jeudy de Grissac, 1989, Fornos and Ahr, 1997). Biogenic carbonate particles were found to be associated with the sandy fraction of sediments (De Falco et al., 2000), and can affect the composition of adjacent beach sediments (De Falco et al., 2003).

Observations of present-day environments in the Balearic low-energy ramp confirmed that *P. oceanica* meadows are associated with shallow sub-tidal carbonate sedimentary facies, mainly composed of mollusk fragments (Fornos and Ahr, 1997). This association was used to interpret the depositional environments of past geological formations (Pomar, 2001). Similar associations were reported in the south Sardinia platforms (Lecca et al., 2005).

On the other hand *P. oceanica* meadows were also observed to colonize sediments of terrestrial origin (Liguria coast, north Italy - Cavazza et al., 2000), and rocky substrates (Western Sardinia - De Falco et al., 2003; Eastern Sicily - Di Carlo et al., 2005), while meadows are generally absent at the mouth of costal rivers, in the depositional area of fine sediments (Pasqualini et al., 1998, De Falco et al., 2006) due to the high sedimentation rate and turbidity which cause a reduction of light penetration. Hydrodynamics may be a relevant factor controlling the sedimentation and growth dynamics of seagrass meadows (Boström et al., 2006). Landscape patterns observed in seagrass habitats are often associated with hydrodynamic disturbances induced by waves (Koch et al., 2006). Losses of *P. oceanica* meadows were observed in coastal areas characterized by long water residence times and therefore by a low renewal capacity (Orfila et al., 2005).

A recent study have been carried out on the relationships between the distribution and growth dynamic of *Posidonia oceanica*, the sedimentary depositional facies (carbonate vs. siliciclastic), and the hydrodynamic features of the Gulf of Oristano (western Sardinia, Mediterranean sea), a complex depositional system characterized by multiple sources of sediments and a marked hydrodynamic gradient (De Falco et al., in press).

Three depositional environments were identified: (i) a poorly vegetated sector characterised by muddy sediments derived from the river input (ii) a sector colonised by *P. oceanica* meadows characterised by biogenic carbonate sediments derived from the sediment production associated with the seagrass ecosystem and (iii) a sector colonised by *P. oceanica* meadows characterised by coarse siliciclastic sediments, possibly relict sediments.

The sedimentary depositional environments are heavily influenced by the spatial distribution of the wind wave energy. Biogenic carbonate reefs associated with *P. oceanica* meadows develop in sheltered areas characterised by low amplitude of waves generated by the main wind regime. In the exposed sectors, characterised by a higher wave height, the meadows colonise relict siliciclastic sediments, without promoting carbonate particle deposition.

P. oceanica meadows in sheltered areas, associated with biogenic sedimentary facies, exhibit higher rhizome growth rate values (1.1 and 1.2 cm year^{-1} vs. 0.7 cm year^{-1}) and a lower percentage of horizontal shoots (1.1 and 4.1% vs. 18%) in comparison to *P. oceanica* meadows in exposed areas, associated with siliciclastic sedimentary facies. The former tend to develop in a vertical direction, thus contrasting the sediment deposition rate, the latter tend to expand laterally due to the absence of sediment deposition.

These results highlight that wave amplitude is the intrabasinal factor which influences the deposition of biogenic sediments and the growth dynamics of *P. oceanica* meadows.

Seagrass meadows and beach dynamics

Despite the very popular statement that seagrass protect beach from erosion, very few studies have analyzed the interactions between seagrass meadow and beach morphodynamic.

P. oceanica have been considered to protect beach from erosion by means of the accumulation of dead leaves cast on the beach that protect beaches form winter storms (Boudouresque and Jeudy de Grissac, 1983). In the sandy shores cast litter form a wedge structures from few centimeters to several meters thick, defined “banquettes” by French authors (Jeudy de Grissac and Audoly, 1985; Boudouresque and Meisnesz, 1982), which are constituted by leaves, rhizomes and sediments (Jeudy de Grissac, 1984).
P. oceanica can protect the beach from erosion by the reef (matte) formed by the meadow in proximity of the meadow upper limit (Jeudy de Grissac, 1984; Jeudy de Grissac and Boudouresque, 1985) which elevate seabed and influence the beach profile shape (Basterretxea et al., 2004)

The concept of shoreface equilibrium profile (even called beach profile) is wide debated among specialist of sandy shore morphodynamic. It is based on the assumption that a beach of specific grain size, if exposed to constant forcing conditions, will develop a profile shape that display no net change in time (Larson, 1991 cited in CHL, 2002, b). Two papers (Jeudy de Grissac and Boudouresque 1985; Basterretxea et al 2004) will be discussed concerning the role of *P. oceanica* reef in influencing beach profile. The mechanisms through which Posidonia meadow regression can alter beach profile and can cause beach erosion, reported by Jeudy de Grissac and Boudouresque (1985), is shown in Figure 1.1 . The basic assumption of the cited author is that meadow regression and reef destruction leave in the shoreface a residual sedimentary layer composed by coarser grain, while rhizomes roots and finer grain are exported outside the shoreface. Consequently the erosion of 1 m of matte will leave a sediment layer 30-40 cm thick.

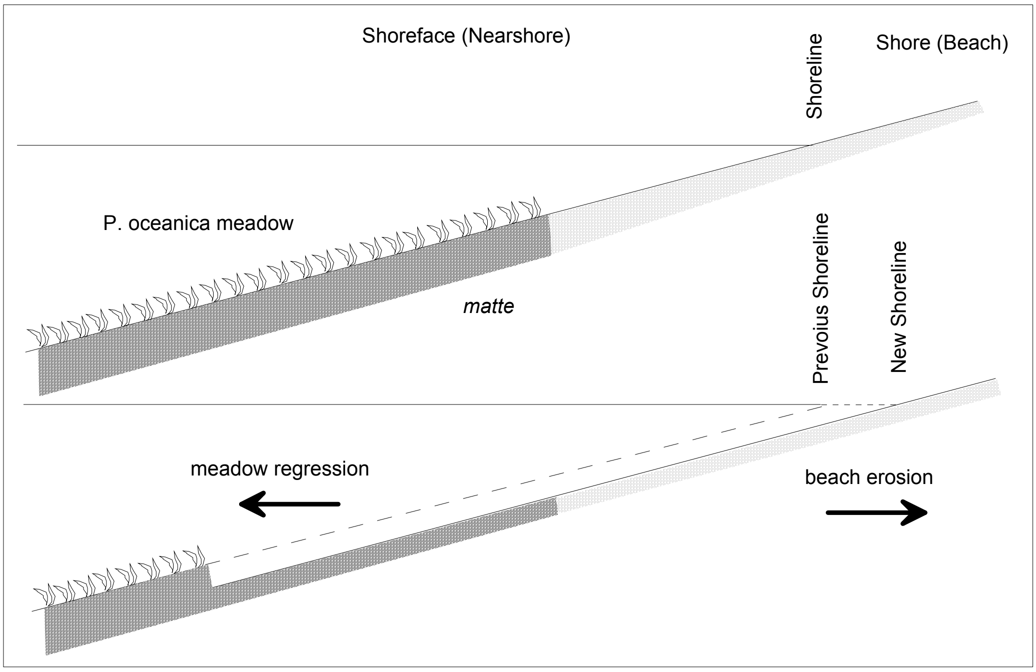

Figure 1.1 Model of beach erosion following *Posidonia oceanica* meadow regression as proposed by Jeudy de Grissac and Boudouresque (1985).

This process lead to an increase of seabed slope. Beach tends to come back to the original slope due to the local hydrodynamic conditions, causing a shoreline retreat as shown in Figure 1.1 (Jeudy de Grissac and Boudouresque, 1984). The author used a very simplified model, assimilating the seabed to a plane, without considering any element of beach morphology.

Basterretxea et al (2004) tried to quantify the effect of Posidonia reef on beach profile. The cross-shore profiles were measured along a pocket beach in Mallorca island for one year. Posidonia meadow was present in the shoreface. The authors infer that the presence of Posidonia meadows conditions the shape of beach profile as consequence of the extra amount of energy dissipated by the meadow which results in steeper form of the beach in comparison to the expected equilibrium profile related to the grain size characteristic of the studied beach.

The presence of Posidonia reef involve an higher values of the dimensionless A shape parameter of the beach profile equation (Dean 1991), compared to the theoretical expected value deriving from the beach sediment grain size characteristics. This is indicative of higher energy dissipation over the Posidonia meadow. As consequences loss of seagrass extent would lead to sediment redistribution toward more dissipative shapes and probably sub aerial beach erosion would follow (Basterretxea et al 2004).

The two papers substantially agreed in considering meadow regression as potential cause of beach erosion, even if the advance of Basterretxea et al (2004) in comparison to Jeudy de Grissac and Boudouresque, (1984) is due to a more rigorous approach with tools derived from beach morphodynamic analysis.

Furthermore very few is know about the relationship between banquettes deposition and backshore profile. Mateo et al. (2003) qualitatively describes the banquettes deposition dynamics and the role of banquettes in protection of beach The authors highlighted that the deposition of leaves starts in end-summer-autumn period, and leaves accumulates during moderate storm event. Banquettes collapse is due to the wave action which provides erosion of its base (Mateo et al, 2003). The same authors affirm that the banquettes could protect the beach from storm of moderate intensity.

In order to summarize the different interaction between the *P. oceanica* meadow and the beach dynamics the Figure 1.2 show this interaction along a typical beach profile.

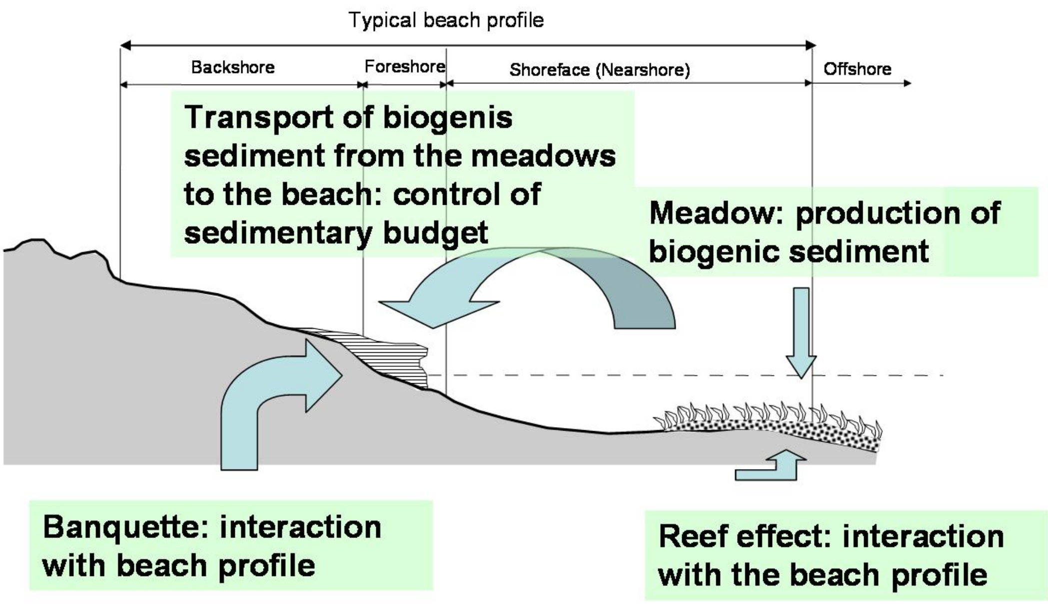

Figure 1.2 : interaction between *P. oceanica* meadows and beach profile

Removal of beach cast P. oceanica leaf litter

Beach-cast seagrass litter deposits are common in many coastal areas where extended seagrass meadows occur. Beach-cast seagrass litter is harvested for biomass exploitation (Kirkman and Kendrick 1997; P.I.R.S.A., 2003) and to improve the recreational use of beaches for tourism (Ochieng and Erftmeijer 1999) in various coastal area all around the world.

In the Mediterranean region, where summer tourism is an important income, the beach-cast *Posidonia oceanica* seagrass litter deposits are often removed because they are believed to reduce the value of beaches mainly for aesthetic reasons (Duarte 2004; Mateo et al., 2003). Removal operation could have a negative impact on the beach geomorphology, on beach sedimentary budget and on nearshore ecosystem in terms of loss of nutritive elements.

1.3 Aim of the study

Aim of this study is investigate the role of *Posidonia oceanica* seagrass beach cast litter deposition on the functioning of coastal systems, in order to evaluate the impact of banquettes removal operations.

The study was done following four specific aims:

(I) to quantify the removed amounts of *P. oceanica* banquettes, as well as the related management practices (i.e., frequency and techniques of removal, dumping) in the island of Sardinia (western Mediterranean). This issue was analyzed and discussed in chapter 2.

(II) to investigate the deposition dynamics and the sediment trapping in the banquettes in beaches with different wave energy conditions in order to evaluate the impact of banquettes removal on the beach sedimentary budget. This issue was analyzed and discussed in the chapter 3.

(III) to analyse the relationships between banquettes deposition and beach geomorphology within beaches characterized by different wave energy conditions (i.e. low vs. high energy beaches), in order to evaluate the impact of banquettes removal on beach geomorphology. This issue was analyzed and discussed in the chapter 4.

(IV) to quantify the nutrient loss for the meadows and the other coastal ecosystems, due to the removal of banquettes in order to evaluate the ecological implications of banquettes removal. This issue was analyzed and discussed in the chapter 5.

Furthermore in the last chapter results from the different studies have been summarized in a general framework in order to suggest management measures.

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CHAPTER 2

Management of beach-cast *Posidonia oceanica* seagrass on the island of Sardinia (Italy, Western Mediterranean)

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Abstract

Removal of beach-cast *Posidonia oceanica* seagrass litter, called banquettes, is a common practice on Mediterranean shores to allow the recreational use of beaches.

Ongoing removal practices of *P. oceanica* banquettes were analyzed on Sardinia island in order to quantify this phenomenon on a broad scale and to evaluate the potential environmental impacts of banquettes removal and dumping on the coastal zone.

Data on banquettes management were collected by means of a questionnaire given to the coastal municipalities and private companies in charge of beach-cleaning operations during 2004.

P. oceanica banquettes removal resulted in a widespread practice applied on 44 beaches (out of 116). Total removed amount for the year 2004 was estimated at 106,180 m^3, heavy machines were generally used to remove banquettes.

Relationships between banquettes removal and beach characteristics showed that higher quantities removed resulted in low energy beaches.

The amount of sediment subtracted to the beach following removal was evaluated by analyzing sand concentration in banquettes collected at three locations. Mean sediment concentration in banquettes was 92.8 kg m^{-3} (C.I. ± 95% 61.3÷124.4 kg m^{-3}; N=60). This value, multiplied for the amount of banquettes removed, allowed us to evaluate the sediment subtracted from each beach between 0.5 to 1,725 m^3. Furthermore the majority (80%) of the volume removed was dumped in non-authorized areas.

Following the findings of the study, some management measures are suggested in order to minimize environmental impact of banquettes removal.

Additional Index Word: *beaches, coastal zone management, leaf litter, banquettes*

2.1 Introduction

Beach-cast seagrass litter deposits are common in many coastal areas where extended seagrass meadows occur. Beach-cast seagrass litter is harvested for biomass exploitation (Kirkman and Kendrick 1997; P.I.R.S.A., 2003) and to improve the recreational use of beaches for tourism (Ochieng and Erftmeijer 1999). In the Mediterranean region, where summer tourism is an important income, the beach-cast *Posidonia oceanica* seagrass litter deposits are often removed because they are believed to reduce the value of beaches mainly for aesthetic reasons (Duarte 2004; Mateo, Sanchez–Lizazo and Romero*,* 2002).

Posidonia oceanica is the main widespread seagrass of the Mediterranean Sea and is endemic of the basin (Pergent, Pergent–Martini and Boudouresque*,* 1995). *P. oceanica* looses leaves in autumn (Chessa et al*.,* 2000; Mateo and Romero 1996; Romero et al., 1992) and the cast litter deposits can be found mainly along sandy coasts, forming wedge structures, from few centimeters to several meters thick, denominated 'banquettes', following the early description reported by French authors (Boudouresque and Meisnesz 1982, Jeudy de Grissac and Audoly 1985).

The depositional dynamic of banquettes is not well known.

Mateo, Sanchez–Lizazo and Romero (2002) pointed out that deposits occur following storm waves after the autumn and that the process depends on the availability of leaf litter. After deposition, erosion occurs at the base of the banquettes which can partially collapse, to be re-deposited in successive storm events. Observations on beaches of the central western coast of Sardinia highlighted that the morphological structures of the beach backshore (ridge, berms, cusps) were often built up of alternating layers of dead *P. oceanica* leaves and sand (De Falco et al., 2003). However data concerning the subsurface stratigraphy of banquettes deposits are not available. Although banquettes have often been said to protect beaches from winter storms (Boudouresque and Jeudy De Grissac, 1983), few studies have been published on this issue.

Banquettes could play a significant role in the shore morphodynamics, and their removal could have an impact on shore stability.

The deposition of banquettes, during autumn, could influence beach morphology and its interaction with waves, modifying the beach profile and reducing sediment movement. Furthermore, banquettes may trap high amounts of sediment (Chessa et al., 2000) and banquettes removal could influence the beach sediment budget.

The aim of this study is to quantify the removed amounts of *P. oceanica* banquettes, as well as the related management practices (i.e., frequency and techniques of removal, dumping) on the island of Sardinia (Western Mediterranean), by collecting data from 116 beaches, for a total length of 289 km distributed along 1900 km of coast.

The relationship between banquettes removal and beach energy characteristics derived from available data (Atzeni et al., 2004; Di Gregorio et al., 2000), as well as the amount of sediment subtracted from beaches with banquettes removal, were estimated in order to evaluate the impact of banquettes removal on coastal geomorphology and the beach sediment budget.

Data on banquettes removal and the related ongoing practices, the impact of banquettes removal on coastal geomorphology and the potential environmental impact deriving from the dumping of the removed material is discussed in order to establish management measures.

2.2 Study site and ongoing management procedures

Sardinia is located in the western Mediterranean Sea (Figure 2.1). The surface of the island is ~24,000 km^2, the total coastal length is 1,896 km 24% of this (458 km) is composed of low, sandy or pebbly shores (Atzeni et al., 2000).

A campaign for the mapping of *Posidonia oceanica* meadows has been realized during the year 2001 with the support of the Italian Ministry for the Environment. The maps are available on line at the Informative System of the Ministry for the Environment (Si.Di.Mar., 2005). Maps downloaded as raster images have been elaborated to obtain the meadow distribution around the Sardinian coast represented in Figure 2.1.

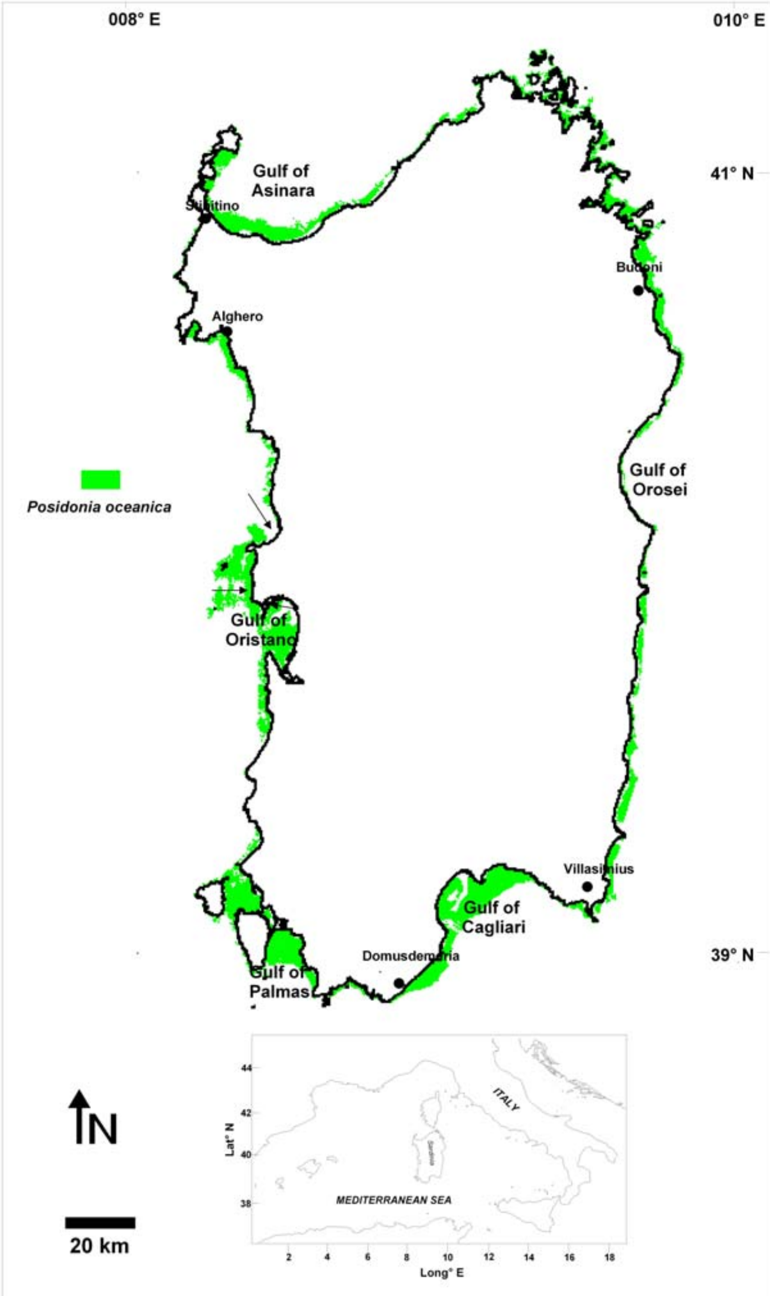

Figure 2.1. Map of Sardinia island showing the distribution of *Posidonia oceanica* meadow (elaborated by the mapping realized by Italian Ministry of Environment, available on-line in the Si.Di.Mar. information system). The arrows show the banquettes sampling locations to analyze the sediment concentration.

P. oceanica meadows are widely distributed along the Sardinian coasts (Figure 2.1). Extended meadows are present in sheltered gulfs and bays (Cagliari, Asinara, Oristano, Palmas) and around small islands. Meadows are limited to a narrow band along linear coastal tracts (e.g. the eastern coast) or are absent in areas subject to strong wind and waves (e.g. the south-western coast). The total extension of the meadow is ca. 1500 km^2, the depth limit is ca. 40 m in offshore clear waters, and is reduced to 15-20 m in inner bays. Studies on beach sediments from the central western coast of Sardinia showed that *P. oceanica* meadows are a source of biogenic carbonate sediments which contribute to beach sediment budget (De Falco et al., 2003).

In the last 30 years, the development of tourism has increased the recreational use of Sardinian beaches which are more often subjected to cleaning operations in order to remove wastes.

Wastes from beaches are considered solid urban wastes by the Italian law (DL n. 22, 5 February 1997, art. 7). Regional Government authorizes the “cleaning” of the beaches by local agencies, coastal municipalities and private companies. Those authorizations generally do not distinguish between waste and *P. oceanica* banquettes. Consequently, The banquettes are normally removed. In some cases, specific authorizations have included *P. oceanica* banquettes in the material which can be removed.

The real amounts of banquettes removed are unknown because a database does not exist. The dumping of the material which results from beach cleaning should follow the procedures for solid urban waste, by means of authorized plants.

An Impact Assessment Evaluation is not required in order to remove the banquettes.

2.3 Methods

Posidonia oceanica banquettes database

A total number of 116 beaches for a total length of 289 km, distributed along the whole Sardinian coast, have been investigated during year 2004.

The climatic condition of year 2004 reflected the average conditions of the region. Rain and temperature were in the range of variability of the previous 30 years (S.A.R., 2005). The wind and the marine circulation of the western Mediterranean are constantly monitored by way of hydrodynamical models (Sorgente et al., 2003). During the year 2004 the wind and the marine circulation were characterized by the typical pattern of the region after the anomalous conditions of the year 2003 (Sorgente, personal communication).

Quantitative data on *P. oceanica* banquettes were collected following the procedures adopted by the South Australian Government (P.I.R.S.A., 2003) which uses an application form which is compiled by the harvester in order to obtain this kind of information. A questionnaire was given out to the technical service of coastal municipalities and to the private entities. The questionnaire requires details on *P. oceanica* banquettes accumulation, removal and dumping, as well as qualitative information on beach erosion evidence, beach frequentation and coastal planning. After the diffusion of the questionnaire, the head person responsible for technical service in each town hall was interviewed by phone. 71 out of 73 towns furnished the required data.

Town halls and private companies know how much volume has been removed because they pay for transport and dumping of banquettes based on the total amount.

Data were inserted into a geographical information system (GIS) using MAPINFO® 7.0 professional software. The GIS was based on a municipality administrative boundaries map. Data derived from the questionnaire were grouped and represented with relation to administrative subdivisions.

Sediment concentration in banquettes

The amounts of sediment removed with the banquettes were estimated by measuring the sediment concentration in three beaches located on the western Sardinia (Figure 2.1).

Those sampling sites have been chosen in order to represent different levels of exposure to dominant waves and different sediment grain size. Two beaches are characterized by high energy of incident waves (Atzeni et al., 2004) and coarse-very coarse sands. One beach is characterized by low energy of incident waves (Atzeni et al., 2004) and fine sands. Banquettes have been sampled collecting 5 samples for beach for season. The sampling operations were carried out during 2005, banquettes removal did not occurred from those beaches during this year.

Sixteen banquettes samples were collected using a cubic box (20 cm per side) for a sampled volume of 0.008 m^3. Leaves were separated from sediments by wet sieving. The remaining fibers were separated from the sediments using a NaCl solution (160 mg l^{-1}).

Sediments were dried and weighed in order to obtain a concentration in kg of dry sediments per m^3 of banquettes.

The concentration data were analyzed with descriptive statistical methods in order to identify mean concentration values and confidence limits.

2.4 Results

Posidonia oceanica banquettes removal

The information obtained for each beach by the questionnaire was grouped considering the boundaries of the coastal municipalities as represented by maps (Figure 2.2).

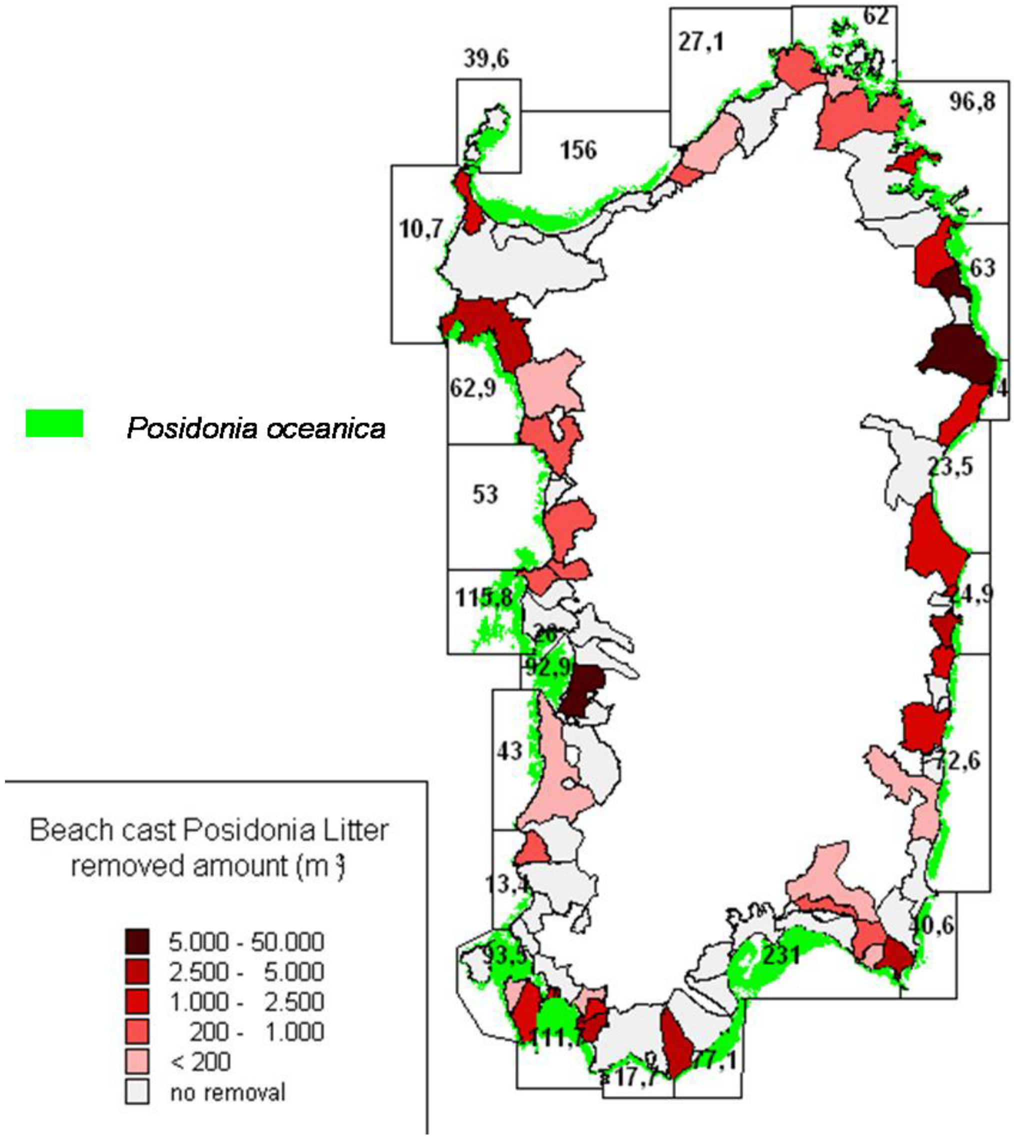

Figure 2.2. Amounts of beach-cast Posidonia litter removed following the questionnaire results. Data have been grouped using administrative boundaries of municipalities in charge of beach clean operations. The surface (km^2) of seabed covered by *Posidonia oceanica* meadows is reported for the marine area, subdivided into 24 sectors. Cartographic representation has been carried out by using a Geographical Information System.

Data were available on the amounts removed, the period and the frequency of removal during the year, the means used for removal, and the dumping procedures for the removed material.

Banquettes removal was carried out on 44 of 116 beaches by 34 coastal municipalities. The other municipalities declared that no removal operations were carried out due to the absence, or presence in very limited quantities, of beach-cast *P. oceanica* banquettes. In one case (the western side of the Gulf of Cagliari) removal was not carried out, even if significant accumulation occurs, because the beach is not used for recreational purposes.

The total removed material was 106,180 m^3 in the year 2004. The amounts removed were represented, divided into six classes.

Greater amounts of banquettes are removed in more tourist areas (Alghero, Budoni, Villasimius) or in sites where heavy accumulation occurs for the presence of extended *P. oceanica* meadows (Figures 2.1 and 2.2). Particularly, 15,000 m^3 of banquettes have been removed in the Gulf of Oristano and 7,700 m^3 have been removed in the Gulf of Palmas. The extension of *P. oceanica* meadows in those bays is respectively 93 and 112 km^2.

The frequency of removal is generally once a year (20 municipalities out of 34). Twelve municipalities remove banquettes more than once a year (in 4 cases with monthly frequency). Two municipalities removed banquettes once in the last 5 years (Figure 2.3).

The removal operations started in April on 9 beaches and in June in most cases (28 out of 44) (Table 2.1). Municipalities which start removal operations in April are the same ones that remove banquettes several times per year.

The removal operations are generally carried out with heavy machines such as bulldozers and front-end loaders and excavators (25 beaches). Removal is carried out by hand on 6 beaches and by beach-cleaning machines on 13 beaches (Table 1).

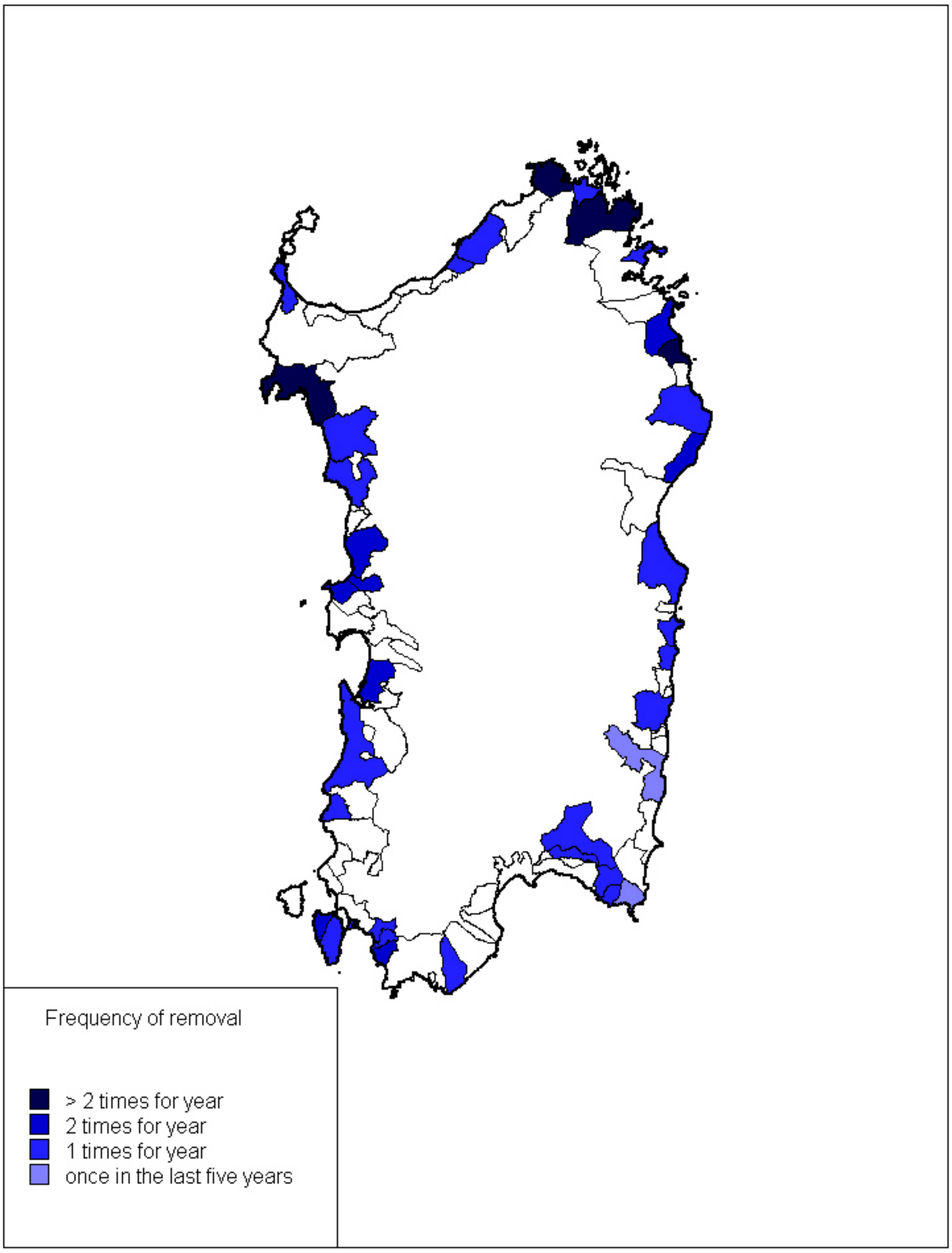

Figure 3. Frequency of removal operations.

The erosion trend of Sardinian beaches is reported in Atlas of Beach (Di Gregorio et al., 2000). The Atlas is constituted by several maps, covering the whole shoreline, indicating evidences of shore advance, stability and erosion. However no indication is given on the causes of erosion.

The comparison of data on erosion trend and data on banquettes removal shows that 77 Km up to 114 Km of beach investigated, where removal operations are carried out, are under erosion. In those beaches, characterized by erosion trend and banquettes removal, the collection of beach cast leaf litter is generally performed with heavy machine (Table 2.1).

Table 2.1. Summary of the data collected with the questionnaire concerning the period of banquettes removal, the means used, the dumping procedures and the beach length under eroding process.

	N° of cases (N=44)	**Removal amounts (total 106,180 m^3)**	**Beach length interested (total 114 Km)**	**Beach length under eroding process (total 77 Km)**
Month of removal				
April	9	50,200	17.6	15.7
May	2	5,000	1.2	0.4
June	28	31,240	78.4	55.2
July	5	19,740	16.9	5.7
Machine used				
By hand	6	230	12.8	8.3
Grid/beach cleaner	13	21,500	41.7	26.7
Front head loader	25	84,450	59.6	41.9
Dumping				
Authorized plant	23	21,700	52.2	
Non Authorized ground	17	35,980	52.2	
Beyond the dune	4	48,500	9.3	

Amount of sediments removed

Few data on sediment concentration in banquettes from Sardinia are available. Chessa et al. (2000) reported concentration values from NW Sardinian coast in the range between 1 to 43 kg m^{-3}. However those values can not be considered representative because they are referred to few samples without seasonal replication.

The sediment concentration in the banquettes samples collected in this study showed a normal distribution with a mean value of 92.8 kg m^{-3} (C.I. ± 95% 61.3÷124.4 kg m^{-3}; Standard Deviation 139.8, N=60).

If we assume those value as the mean sediment concentration in banquettes, we can compute the sediment volume subtracted to the beaches following removal operations. The sediment volume subtracted from each beach was obtained by assuming a bulk sediment density of 1.7 ton m^{-3} (CHL, 2002) while converting mass to volume. The sediment volume subtracted fluctuates from 0.5 to 1,725 m^3, and is higher than 200 m^3 for seven beaches (out of 44), between 50 and 200 m^3 for 14 beaches, lower then 50 m^3 for 23 beaches.

Dumping of removed material

The disposal procedures vary between municipalities (Table 2.1). Fourteen municipalities (23 beaches out of 44) stock litter in authorized plants for solid urban wastes while 16 municipalities (17 beaches) claim to move the material to other sites (fields, quarries, etc.). Four municipalities (4 beaches) dump the removed material behind the dune. However, considering the subdivision of disposed amounts it comes out that 46% of the removed material (48,500 m^3) is deposited behind the dunes, 34% (35,980 m^3) in non-authorized sites, and only 20% (21,700 m^3) in authorized plants. This is due to the fact that it is impossible for the municipalities which must remove great amounts of material to afford the high cost of proper dumping.

2.5 Discussion

P. oceanica banquettes removal is a diffused practice in Sardinia and is applied along 114 km of beaches out of the 289 km of sandy shore considered in this study. This practice is diffused in other Mediterranean sites in order to allow for the recreational use of beaches (Duarte 2004, Mateo, Sanchez–Lizazo and Romero, 2002) and better management needs to be put into place to avoid environmental impact on the coastal zone.

The comparison between the banquettes removed amounts and the mean annual energy of beaches available from previous studies (Atzeni et al., 2004), shows that banquettes removal rate has been found to decrease with annual energy increase (Figure 2.4). Particularly, the removal rate is inversely related to the mean annual energy transferred by waves on the beach (Atzeni et al., 2000).

The annual energy have been computed by Atzeni et al. (2000) by computing the wind waves from meteorological data and the energy transferred by waves onto the beach by means of the methodology proposed in the Shore Protection Manual (CERC, 1984).

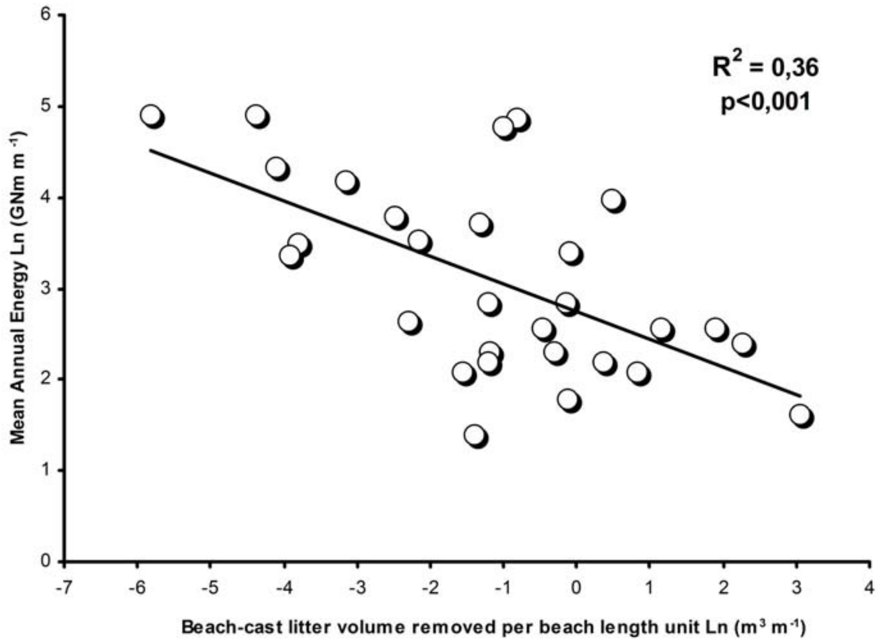

Figure 4. Relationship between banquettes removal rate (m^3 per beach length unit $–m^{-1}$) and Mean Annual Energy (GNm m^{-1}) derived by Atzeni et al. (2004). Data are expressed as natural logarithms.

The higher accumulation rates of *P. oceanica* banquettes occurring in lower energy beaches could be explained by the major extension of *P. oceanica* meadow in sheltered coastal sites. Furthermore banquettes deposits are less subjected to wave action in low energy beaches and can consequently stay on these beaches over longer periods. This would confirm the observations reported by Jackson et al., (2002) that vegetation litter is mainly deposited on low energy beaches.

Beach morphology is the result of interaction between different factors (i.e. wave climate, nature of the sediment, geological control). High energy beaches can be characterized by marked seasonal changes between summer and winter, depending on the variability of the wave climate, with variations from a reflective to a dissipative condition from summer to winter (Jackson et al., 2002). Such variations involve cross-shore sediment transport from the emerged to the submerged beach and a retreat of the shoreline during the winter (Coastal and Hydraulics Laboratory, 2002; Komar, 1998). On the other hand, low energy beaches are characterized by minor seasonal changes and sediment transport rates (Jackson et al., 2002). Low energy beaches are generally characterized by a narrow backshore, a low cross-shore sediment exchange and a steep foreshore (Jackson et al., 2002). Beach-cast litter influences the geomorphic evolution of low energy beaches under non-storm conditions, influencing beach topography and creating zones of accretion and scour in contrast to the rhythmic features common in high energy beaches (Jackson et al., 2002).

Banquettes removal from low energy beaches during winter and spring could expose beaches to erosion following severe storm events with a change in beach morphology. Post-storm beach recovery on low energy beaches occurs at a slow rate (Jackson et al., 2002) and consequently the impact of banquettes removal before a storm event could have an effect on beach morphology for long period of time.

Furthermore, banquettes removal could influence the beach sediment budget due to the sediment subtraction. The length of 21 beaches (out of 44), where banquettes removal is carried out, does not exceed 1 km. Low sediment supply is provided to Sardinian beaches from rivers due to the presence of dams in all main rivers. Consequently the annual subtraction of hundreds of cubic meters of sediments from the beaches could significantly affect the sediment budget.

On the other hand the removed sediment could be higher of the amount evaluated in this study, because removal is done with heavy machines (i.e. bulldozers, front head loaders) which easily collect the sediment underlying the banquettes.

As for the dumping of removed litter, our data showed that 80% of the volume removed was discharged in non-authorized plant and 20% was treated as urban waste. The cost of urban waste disposal is ca. 100 Euro/ton, bringing us to a total cost of more than 2 million Euros, if all removed material is treated in authorized plants. All fees for removal and transport would be in addition to this estimation. These expenses are the responsibility of the municipalities involved, and in a very few cases are paid by private tour operators This is probably the main reason for which disposal is made in non- authorized areas and behind the dunes.

There are few indications from environmental agencies of the Mediterranean region related to the management of beach-cast Posidonia litter. Examples from other regions of the world have been evaluated in order to identify some management guidelines.

Beach-cast seagrass litter is harvested for biomass exploitation in South Australia (Kirkman and Kendrick 1997; P.I.R.S.A., 2003) and this activity is regulated by the South Australian Government (P.I.R.S.A., 2003) in order to minimize the impact of beach-cast seagrass and seaweeds litter removal and disposal.

In particular the South Australian Government identified the potential impacts of seagrass and seaweed harvesting and the alteration of coastal geomorphology as an ecological impact on the coastal ecosystems and a loss of habitat for birds (Kirkman and Kendrick 1997; P.I.R.S.A., 2003). The management of seagrass harvesting in South Australia is subjected to environmental impact assessment and to specific rules summarized in Table 2.2.

The comparison between P.I.R.S.A. recommendations and the ongoing management procedures in Sardinia resulted form this study (Table 2.2), evidences that recommendations adopted in South Australian are not currently followed for Sardinia beaches.

There are clear differences between the Australian and Mediterranean beaches, however the general guidelines proposed by P.I.R.S.A. (2003) can be easily adapted to improve the management of banquettes removal in the Mediterranean region.

Particularly the following measures for minimizing the impact on the coastal zone by *P. oceanica* banquettes removal could be adopted:

(i) Removal should be avoid during winter and spring, when storm events could occur, the use of heavy machinery should be limited and vehicular access regulated. Those measures minimize the impact on beach geomorphology.

(ii) The removed material should be sieved and a layer of Posidonia (i.e. 10 cm thick) should be left on the beach in order to limit sand subtraction.

(iii) As for dumping, it is preferable to create temporary sites in which to store the leaf litter to decompose for up to several years until it is suitable as a soil improver. Recycling the seagrass litter would partially compensate for the cost of removal while avoiding the costs of dumping it as urban waste.

Management measures could include requiring an Evaluation Impact Assessment procedure before allowing the banquettes removal.

Table 2.2. Comparison between management issues of beach-cast seagrass harvesting adopted in South Australia (P.I.R.S.A., 2003) and the ongoing management procedures for *Posidonia oceanica* banquettes removal in Sardinia as resulted from this study.

	Potential impact	**Recommendations by P.I.R.S.A. (2003)**	**Results from this study**
Coastal Geomorphology	Beach erosion due to changes in beach morphodynamic behavior.	Limiting the use of heavy machinery, restricting vehicular access to the beach via established tracks. Removal limited to beyond 4 meters from the toe of the fore-dune, and not allowed from below the low water mark.	Heavy machines are mainly used, the access to the beaches is not regulated. Banquettes are removed from low energy beaches, from the foreshore up to the toe of the dunes.
	Beach erosion due to subtraction of sediment.	Direct removal of sand prohibited; To leave 10 cm covering of seagrass on the beach.	Sediment trapped in banquettes and subtracted from the beaches is > 50 m^3 for 21 beaches (out of 44). The entire deposit of beach-cast Posidonia leaf is generally removed.
Disposal of removed material	Production of waste.	Storage of seagrass wrack in paddocks to allow decomposition for several years before it is suitable for use as a soil improver or garden mulch.	80% of removed material is dumped in non-authorized areas.

2.6 Conclusions

1. Posidonia banquettes removal is a diffused practice along the coast of Sardinia and is carried out on 40% (114 km) of the sandy shore analyzed in this study. 68% (77 km) in length of sandy shore where removal is carried out are under erosion (Atzeni et al., 2004; Di Gregorio et al., 2000). The amounts removed are higher on low energy beaches. Banquettes removal in spring accompanied by sediment subtraction may lead to beach erosion. The dumping of the removed material was done mainly in non-authorized plants (80% of the total amount).
2. The management issues deriving from the findings of this work can be used as guidelines for the adoption of an Evaluation Impact Assessment procedure, in order to minimize the impact of banquettes removal on costal geomorphology, and to improve the management of the removed material.

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2.7 References

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CHAPTER 3

Deposition dynamics and sediment trapping in beach cast *Posidonia oceanica* seagrass litter

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Abstract

Posidonia oceanica seagrass litter are commonly found along sandy shores in the Mediterranean region. They form wedge structures called 'banquettes', which are often removed in order to "improve" the beach for tourists.

This study investigates the deposition dynamics and sediments trapped in the banquettes on three beaches on the western coast of Sardinia (western Mediterranean) characterized by different wave energy conditions. Field measurements of banquettes volume were calculated using a Real Time Kinematic Differential Global Positioning System. Banquettes sampling was carried out in two different periods of the year, before and after the fall of *P. oceanica leaves*, and at two levels of the beach profile (i.e. foreshore and backshore). The sampling was aimed at analyzing rhizome biomass and sediment concentrations

The high energy beaches showed higher mean volumes of banquettes deposited during the year (1603±500 and 1815±1799 m^3) in comparison with the low energy beach (188±123 m^3).

Rhizomes were not found in the banquettes on the low energy beach. The rhizomes biomass was found to be higher on the backshore than on the foreshore (0.15 ± 0.07 kg kg^{-1} vs. 0.05 ± 0.02 kg kg^{-1}) after the leaves fall on high energy beaches. The sediment concentration in the banquettes was always higher on the backshore than on the foreshore (82.2 ± 55.7 kg m^{-3} vs. 20.3 ± 21.9 kg m^{-3}), and is independent from wave energy.

Banquettes deposition occurs during the final phases of a storm event, when wave energy decreases. The landward limit of banquettes marks the maximum wave run-up, where heavier materials are deposited leading to higher sediment concentrations on the backshore. The development of wider and thicker banquettes on high energy beaches in comparison with the low energy beach is due to the wider swash zone.

Based on the findings of this study, the impact of banquettes removal on the sedimentary budget of Mediterranean beaches was discussed.

Keywords : Banquettes, *Posidonia oceanica*, seagrass, beaches, sediment

3.1 Introduction

Seagrasses cover about 0.2 % of the world's oceans, and develop highly productive ecosystems (Duarte, 2002). Most of the production, due to the aboveground compartment (i.e. leaves) becomes litter, that can decompose within the meadow, be exported to other ecosystems or accumulated in adjacent shorelines (Walker at al., 2001).

Posidonia oceanica Delile (L.) is the most widespread seagrass species of the Mediterranean sea (Pergent et al., 1997). It can form large meadows from the surface of the sea down to a depth of 40 m (Boudouresque, 1990). A regular loss of *P. oceanica* leaves has been described in late summer-early autumn in many different regions in the Mediterranean Sea (Mateo and Romero, 1996; Romero et al., 1992). On the sandy shores, cast litter forms wedge structures from a few centimeters to several meters thick which have been defined "banquettes" by French authors (Jeudy de Grissac and Audoly, 1985; Boudouresque and Meisnesz, 1982). These are made up of leaves, rhizomes and sediments (Jeudy de Grissac, 1984).

The deposition dynamics of banquettes have been qualitatively described by Mateo et al. (2003), who infer that they offer a considerable resistance against the wave action (Mateo et al., 2003). Furthermore *P. oceanica* beach cast litter can be found inside the morphological structures of the backshore (berms and beach ridges) and thus contributes to the beach morphology (De Falco et al., 2003).

Beach cast vegetation litter is generally more abundant on low energy beaches, while on high energy beaches the litter is often in patterns which are representative of individual swash uprushes (Jackson et al., 2002).

Beach-cast vegetation litter is harvested for biomass exploitation (Kirkman and Kendrick, 1997) and to improve the recreational use of beaches for tourism (Ochieng and Erftmeijer, 1999) in various coastal areas all around the world.

P. oceanica banquettes are currently removed in order to favor the use of the beach for tourist activities over the entire Mediterranean region (Duarte, 2004). About 106,000 m^3 of banquettes have been removed from 114 km of beaches, during 2004, on the island of Sardinia (Western Mediterranean), mainly by using heavy machinery (De Falco et al., 2007).

Variable amounts of sediments can be trapped inside banquettes, with concentrations in the order of 10-100 kg m^{-3} (De Falco et al., 2007; Chessa et al., 2000). Consequently, banquettes removal could affect the sedimentary budget of the beach.

Very little is known about the depositional dynamics of banquettes and their capacity to trap sediments as a function of beach characteristics. Different amounts of sediments inside the banquettes could be related to the energy conditions of the beach. Moreover, the seasonal fall of *P. oceanica* leaves which occurs in late summer early autumn (Romero et al., 1992) may also account for different amounts of sediments inside the banquettes.

The aim of this study was to investigate the deposition dynamics and the sediment trapping in the banquettes on beaches with different wave energy conditions.

The total volume, rhizome biomass and sediment concentrations of the banquettes were analyzed in two different periods of the year, before and after the fall of *P. oceanica leaves*, and at two levels of the beach profile (i.e. foreshore and backshore).

Finally, indications on the impact of banquettes removal of *P. oceanica* on the sedimentary budget of Mediterranean beaches were given .

3.2 Materials and methods

Study sites and beach sediment characterization

The study area is located on the central western coast of the island of Sardinia (western Mediterranean) (Figure 3.1a). In this sector of Sardinia, north west winds (Mistral) are dominant throughout the year (Pinna, 1989) and the dominant wave direction is 305° North degrees (Atzeni et al., 2003).

Extended *Posidonia oceanica* meadows are widespread in the area, and are associated with a sandy substrate in the Gulf of Oristano and a rocky substrate in the outer sea (Figure 3.1a) (Tigny et al., 2007; De Falco et al., 2003).

Three beaches, all characterized by the deposition of *P. oceanica* banquettes, were chosen as study sites. Is Arenas beach is ca. 7 km long, it is oriented NE-SW and is approximately normal to the dominant wave rays. The mean annual energy of wave motion here is 138 GNm m^{-1} (Atzeni et al., 2004). *P. oceanica* meadows are absent in front of the beach, but are present in the northern coastal sector. Consequently, banquettes deposition occurs on the northern part of the beach.

Maimoni beach is oriented NS. The mean annual energy of wave motion here is 118 GNm m^{-1} (Atzeni et al., 2004). *P. oceanica* meadows extend far in front of the beach, with a substrate characterized by a thick sediment layer (ca. 50 cm) on a rocky bottom (De Falco et al., 2003).

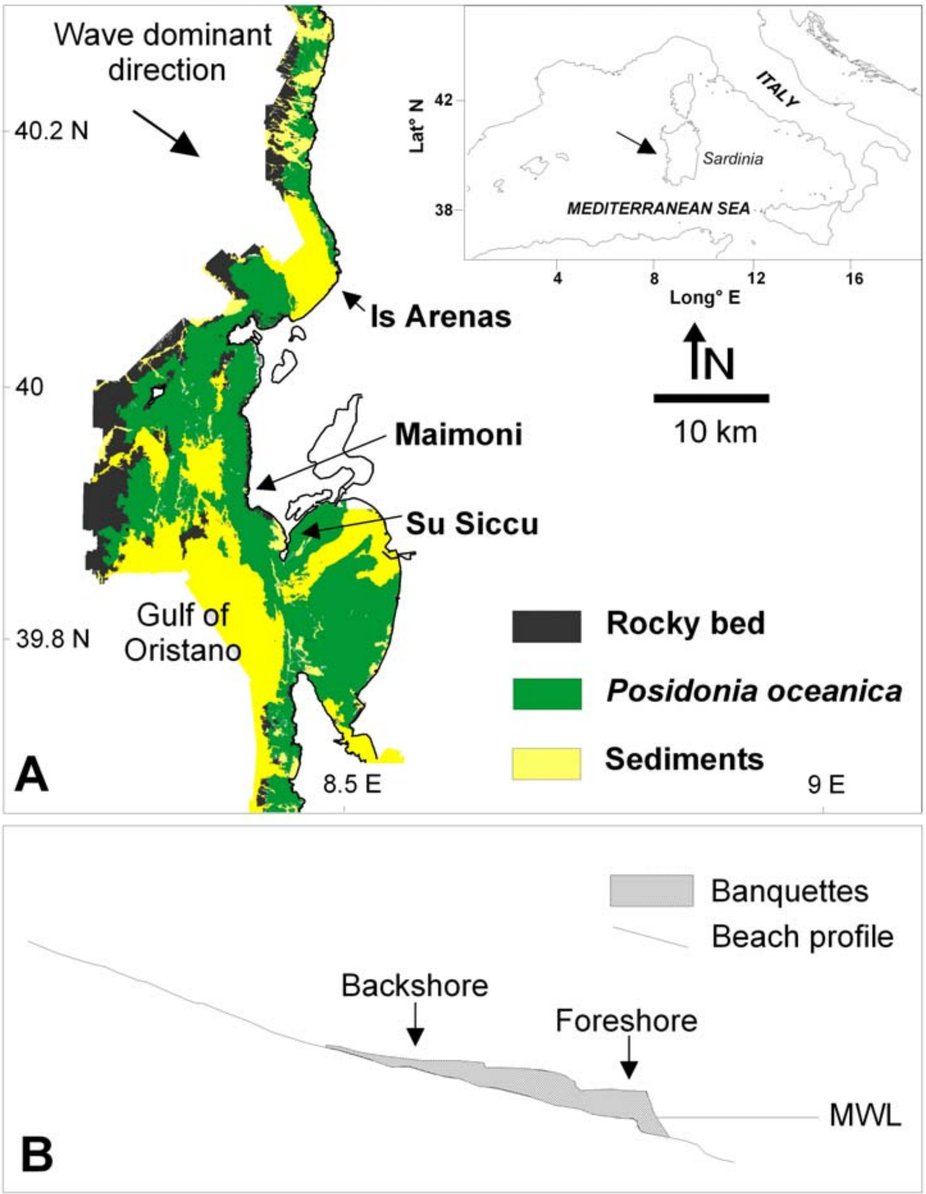

Figure 3. 1 (a) Map of the study area showing the location of studied beaches, the map of *Posidonia oceanica* meadow were Published by AA. VV. (2005); (b) scheme of the beach profile showing the sampling positions of banquettes.

Su Siccu beach is located inside the gulf of Oristano to the south, with 1 GNm m^{-1} of mean annual wave motion energy (Atzeni et al., 2004). *P. oceanica* meadows over a muddy and sandy substrate is common in this sector of the gulf (De Falco et al., 2000).

Following the values of the mean annual wave motion energy Is Arenas and Maimoni can both be considered high-energy beaches (hereafter called HEn1 and HEn2) while Su Siccu can be considered a low-energy beach (hereafter called LEn).

In order to determine sediment grain size, sediment cores (10 cm diameter up to 10 cm deep in the sediment) were collected at three randomly chosen stations on both foreshore and backshore at each beach on all sampling dates. The foreshore sediment samples were collected below or in front of banquettes, the backshore samples were collected below the banquettes (Figure 3.1b).

In the laboratory, sediment cores were thoroughly washed with distilled water and oven dried at 80° C for 12 hours. Grain size analysis was performed by dry sieving for the coarser fraction (< 1 phi) and by laser analysis (Galai Cis 1 laser system, liquid flow mode) for finer sand (De Falco et al., 2003).

Beach sediment grain size data were represented using bivariate plots of statistical parameters of grain size distribution (mean, sorting, skewness), which were computed using the momentum method (Blott and Pye, 2001).

Sampling design

This study was carried-out from March 2005 to March 2006. The following variables were considered: (i) volume of banquettes, (ii) rhizome biomass (kg kg^{-1} dry weight) and (iii) sediment concentration (kg m^{-3}) in banquettes. The rhizome biomass and sediment concentration supplied information on the depositional dynamics and sediment trapping capacity of banquettes.

At each beach (i.e., HEn1, HEn2 and LEn), two sampling dates were randomly chosen respectively before and after the period in which the *P. oceanica* leaves fall (hereafter called Before-I, Before-II, and After-I and After-II). At each beach and sampling date the total volume of banquettes was measured, and banquettes samples were collected at two levels of the beach profile: the foreshore and the backshore (Figure3.1b).

Data collection and laboratory analysis

Topographic surfaces of both beaches and banquettes were measured using a Real Time Kinematic (RTK) – Differential Global Positioning System (DGPS) (Haxel and Holman, 2004; Dail et al., 1999; Morton et al., 1993). The DGPS method ensures good accuracy in measuring the vertical position (<7 cm) as well the horizontal position (<5 cm).

Ground elevation data of the beach sector where banquettes occurred were collected using a small vehicle that keeps the DGPS antenna at a fixed height from the ground.

Position data (X,Y and Z) were acquired in Real Time Kinematic (RTK) modality along a series of transects spaced about 5 meters apart, which were perpendicular and parallel to the shoreline. RTK allows for the collection of the position (X,Y and Z) of a single point per second.

Elevation data of the beach below the banquettes were collected using the Stop and Go modality, which allows one to acquire the position of a single point. The DGPS antenna was mounted on a steel pole, which was driven into banquettes down to the interface between sediment and banquettes, in order to acquire the point positions (X,Y and Z). The position of the interface between sediment and banquettes was acquired at different points along a series of transects which were perpendicular and parallel to the shoreline and spaced 5 meters apart. The distance between two contiguous points on each transect was ca. 2 meters.

At each beach and sampling date, banquettes sample were collected at two levels of the beach profile, the foreshore and the backshore (Figure 3.1b). Two replicate samples were collected using a cubic box of volume 0.008 m^3 pushed into the banquettes at four randomly chosen stations at each beach.

The banquettes samples were wet sieved (2.5 mm mesh) to separate leaves and rhizomes from the sediment. The rhizomes were then manually separated from the leaves. The sediment was further separated from the remaining fibers using a saline solution (160 mg l^{-1}). Rhizomes, leaves and fibers were oven-dried at 50 °C for a week and weighed in order to measure the rhizome biomass. Sediments were then dried (105 ° C for 48 h) and weighed to determine sediment concentration in banquettes (Kg m^{-3}).

Data analysis

The elevation surface of the banquettes, and the elevation of the surface of the interface between sediment and banquettes,(as digital elevation models), were obtained by means of a natural neighbor interpolation procedure of elevation data acquired by DGPS using SURFER package (Golden Software®). The volume tool of the interpolation software allows one to compute the volume between two different surface levels, which in this case is equivalent to the volume of the banquettes.

Differences in rhizome biomass and sediment concentration were tested separately on each sampling dates using a 3-factor mixed model ANOVA (Underwood, 1997). The factors included in the analyses were: *Beaches* (fixed with 2 levels for rhizome biomass and 3 levels for sediment concentration), *Foreshore vs. Backshore* (*F vs. B*; fixed and orthogonal to *Beaches*), and *Stations* (*St*; random and nested to *F vs. B x Beaches*) with 4 levels. There were 2 replicates. Homogeneity of variances was checked using Cochran's C-test and, whenever necessary, data were appropriately transformed to remove the heterogeneous variances and newly tested (Winer et al., 1991). In the analyses of variance, when significant effects of *Beaches*, *Foreshore vs. Backshore* or their interaction were found the a posteriori Student-Newman-Keuls (SNK) test was used.

The total sediment mass trapped in the banquettes was estimated by the product of the banquettes volume and the mean sediment concentration. Sediment mass was converted into sediment volume by assuming a sediment bulk density of 1.7 tons m^{-3} (King and Galvin, 2002).

3.3 Results

Beach sediment characterization

The bivariate plots of the statistical moments of grain size curves of beach sediments for the different sampling periods (before and after leaves fall) were reported in Figure 3.2.

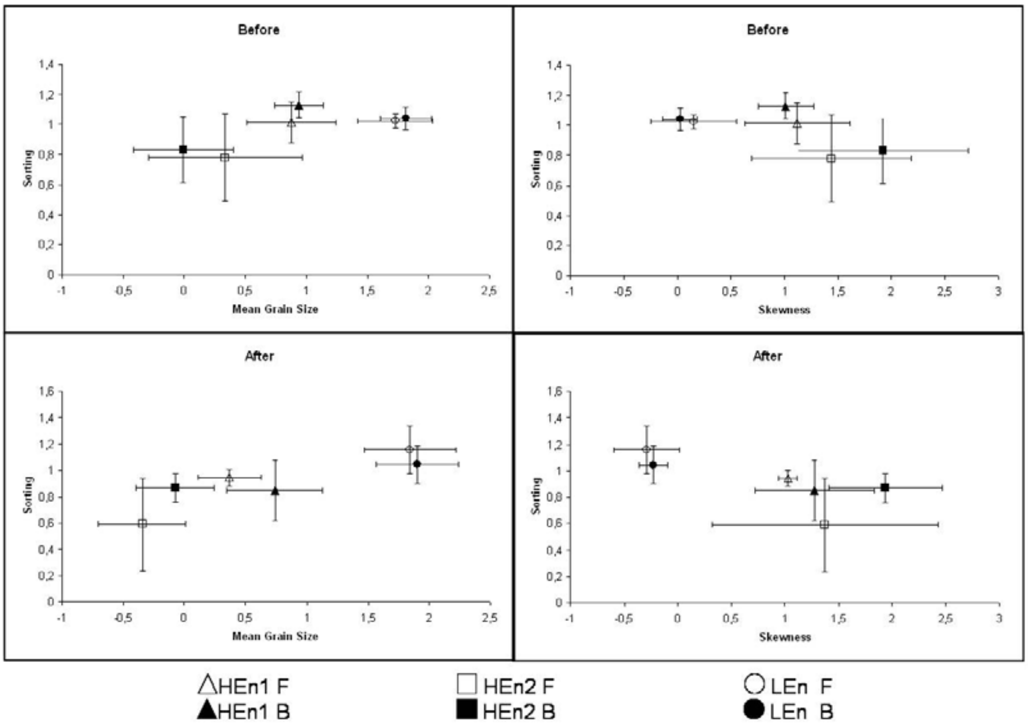

Figure 3. 2 Bivariate plots of grain size statistical moments of beach sediment.

The low energy beach (LEn) is clearly separated from the other beaches (HEn1 and HEn2) and is characterized by finer sediments (medium-fine sands) with a nearly symmetrical grain size distribution. The sorting of LEn sediments is approximately constant in samples collected in the different periods.

The high energy beaches show a coarser grain size (from medium to very coarse sands) with a positive skewness. Sorting values decrease from the samples collected before the leaves fall and samples collected after the leaves fall.

Volume, rhizome biomass and sediment concentration of the banquettes

The mean volumes of banquettes (m^3) at each beach were reported in table 3.1. High energy beaches showed a higher mean volume of banquettes deposited during the year (1603±500 and 1815±1799 m^3) in comparison with the low energy beach (188±123 m^3). During the late spring – summer period banquettes deposition did not occur at the HEn1 beach.

Table 3.1. Descriptive statistics of banquettes volume on investigated beaches

		Beaches		
		HEn 1 (n=3)	**HEn 2 (n=4)**	**LEn (n=4)**
Volume of Banquettess (m^3)	Mean ± S.D.	1603 ± 500	1815 ± 1799	188 ± 123
	Range	1127 ÷ 2124	277 ÷ 4400	95 ÷ 365
Banquettes volume for unit beach length ($m^3 m^{-1}$)	Mean ± S.D.	3,1 ± 1,3	6,2 ± 4,9	1,7 ± 1,1
	Range	2,2 ÷ 4,6	2,6 ÷ 13,1	1,0 ÷ 3,4
Maximum width of banquettess (m)	Mean ± S.D.	13,0 ± 6,0	15,5 ± 2,1	5,8 ± 2,9
	Range	7,0 ÷ 19,0	13,0 ÷ 18,0	4,0 ÷ 10,0
Maximum thickness (m)	Mean ± S.D.	1,4 ± 0,4	1,5 ± 0,7	0,3 ± 0,1
	Range	1,0 ÷ 1,6	0,7 ÷ 2,2	0,2 ÷ 0,4

Banquettes accumulation rate was computed as the ratio between banquettes volume and the length of the beach where the deposition occurred (Table 1). Higher accumulation rates were detected for high energy beaches (3.1 ± 1.3 and 6.2± 4.9 m^3 m^{-1} vs. 1.7 ± 1,1 m^3 m^{-1}), where banquettes showed a greater thickness (1.4 ± 0.4 and 1.5 ± 0.7 m vs. 0.3 ± 0.1 m).

Rhizomes were not found in the banquettes of the low energy beach (LEn) at any of the sampling dates (Figure 3.3). As a consequence, this beach was excluded from the analyses of variance (see the footnote at table 3.2 for the details of the test). The analyses of variance did not reveal differences in the rhizome biomass in the factors of interest before the period of the fall of the leaves (table 3.2a,b; Figure 3.3). On the contrary, significant differences of *Foreshore vs. Backshore* were found on the two sampling dates after the leaves fall(*F. vs. B.* in table 3.2c,d;

Figure 3.3). Similarly, the rhizomes biomass was found to be higher on the backshore than on the foreshore for the two high energy beaches, (SNK test $p<0.05$ in table 3.2c,d and Figure 3.3).

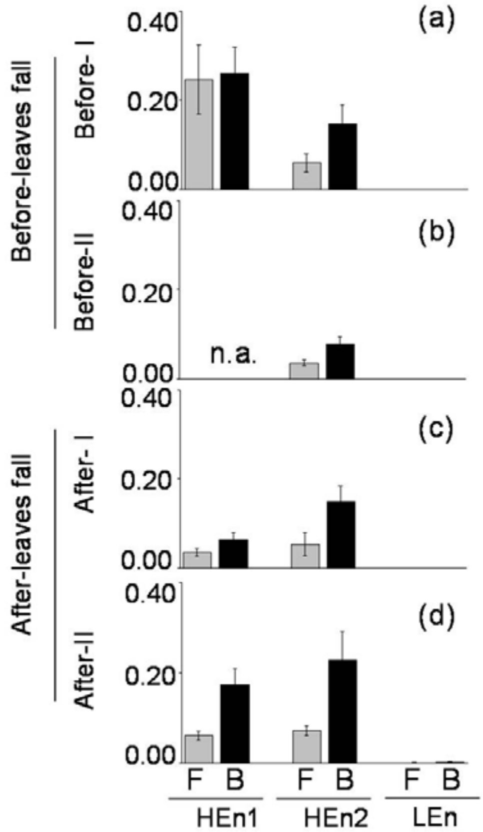

Figure 3. 3 Rhizome content in foreshore and backshore samples of banquettes on the four sampling dates.

The analyses of variance and SNK test revealed that the major changes in sediment concentration occurred along the beach profile. The sediment concentration in the banquettes was always higher on the backshore than on the foreshore (table 3.3 and Figure 3.4). This general pattern was consistent among the beaches investigated on the two sampling dates before the fall of the leaves. The main factor *Foreshore vs. Backshore* (*F. vs. B.* and SNK test, $p<0.05$ in table 3.3a,b; Figure 3.4) was found to be significant.

After the leaves fall, significant effects of *Beaches x Foreshore vs. Backshore* interaction term were found (*Beaches x F. vs. B.* in table 3.3c,d). Those results are due to significant differences in sediment concentration among beaches at the same level of the beach profile (foreshore and backshore) (SNK test $p<0.05$ in table 3.3c,d; Figure 3.4).

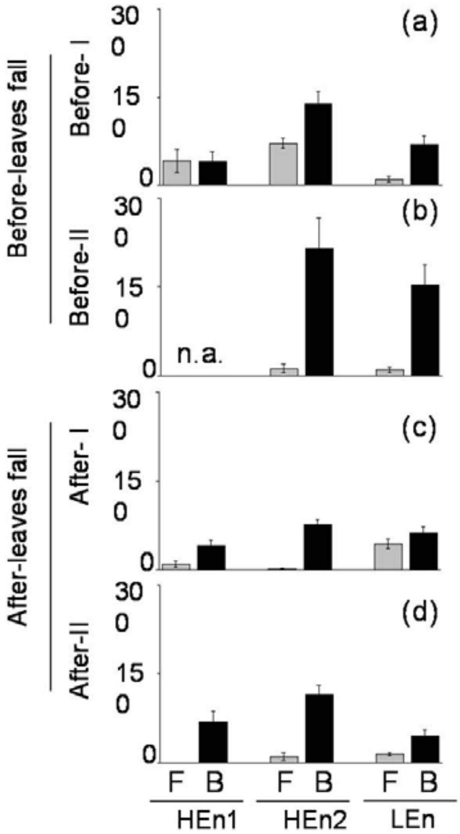

Figure 3. 4 Sediment concentration in foreshore and backshore samples of banquettes on the four sampling dates.

Finally, significant differences were found between *Stations* at each sampling date for rhizome biomass as well as for sediment concentration (except the first and second sampling dates after the leaves fall, respectively) (*Stations(Beaches x F vs.B)* in Tables 3.2 and 3.3), indicating a high variability at this spatial scale for both these variables.

Table 3.2 Analyses of variance and SNK test results on rhizome biomass (kg kg^{-1}) at each sampling date Before- and After-leaves fall. Data were arc sin % transformed. Probabilities of relevant tests are indicated in bold. The contrast *Foreshore vs. Backshore* = *F vs. B*; Beaches: HEn 1, HEn 2 and LEn.

Source of variation	Pre leaf fall						Post leaf fall					
	(a) Before-I			(b) [3]Before-II			I After-I			(d) After-II		
	d.f	MS	F	d.f	MS	F	d.f	MS	F	d.f	MS	F
Beaches	1	8.13	2.63				1	1.73	3.98	1	0.23	0.28
F vs.B	1	2.28	0.74	1	1.02	3.48	1	3.30	**7.61***	1	7.76	**9.67****
Beaches x *F vs.B*	1	0.21	0.07				1	0.87	1.98	1	0.02	0.03
[1] Stations(*Beaches* x *F vs.B*)	12	3.09	44.49***	6	0.29	6.99**	12	0.43	0.88	12	0.80	3.17*
[2] Residual	16	0.07		8			16	0.49		16	0.25	
							SNK test			SNK test		
							F vs.B *Foreshore < Backshore*			*F vs.B* *Foreshore < Backshore*		

[1] Denominator of *F vs.B*, *Beaches* and *Beaches x F vs.B*
[2] Denominator of Stations(*Beaches x F vs.B*)
[3] Data from HEn 1 was not available at this sampling date. *F vs.B* was tested only at HEn 2 using a two-way model ANOVA (Underwood, 1997), with *F vs.B* (fixed), and Stations (random, nested in *F vs.B*; 4 levels) as factors, and two replicates.
* P<0.05, ** P<0.01, *** P<0.001

Table 3.3 Analyses of variance and SNK test results on sediment concentration (kg m^{-3}) at each of the two sampling dates of Before and After leaves fall. Except After-I date (un-transformed data), data were log (x + 1) transformed. Probabilities of relevant tests are indicated in bold. The contrast *Foreshore vs. Backshore* = *F vs. B*; Beaches: HEn 1, HEn 2 and LEn.

	Before leaves fall						After leaves fall					
Source of variation	(a)	Before-I		(b)	Before-II		I	After-I		(d)	After-II	
	d.f	MS	*F*	d.f	MS	*F*	d.f	MS	*F*	d.f	MS	*F*
Beaches	2	19.02	5.56*	[3]1	8.89	0.27	2	3047.61	3.53	2	31.71	9.04**
F vs.B	1	16.20	**4.74***	1	786.82	**23.91*****	1	20996.36	24.31	1	336.48	95.97***
Beaches x *F vs.B*	2	4.61	1.35	1	14.12	0.43	2	3400.84	**3.94****	2	26.84	**7.65****
[1] Stations(*Beaches* x *F vs.B*)	18	3.42	8.68***	12	32.90	21.08***	18	863.82	3.30**	18	3.51	1.67
[2] Residual	24	0.39		16	1.56		24	261.89		24	2.10	
	SNK tests			SNK tests			SNK tests			SNK tests		
	F vs.B			*F vs.B*			*Beaches* x *F vs.B*			*Beaches* x *F vs.B*		
	Foreshore < *Backshore*			*Foreshore* < *Backshore*			d.f.= 2,18; SE=10.39			d.f.= 2,18; SE=9.66		
							F vs.B (*Beaches*)			*F vs.B* (*Beaches*)		
							HEn 1: *Foreshore* < *Backshore*			HEn 1: *Foreshore* < *Backshore*		
	Beach						HEn 2: *Foreshore* < *Backshore*			HEn 2: *Foreshore* < *Backshore*		
	HEn 1=LEn< HEn 2						LEn: n.s.			LEn: *Foreshore* < *Backshore*		
							Beaches(*F vs.B*)			*Beaches*(*F vs.B*)		
							Foreshore: HEn 1= HEn 2<LEn			*Foreshore*: n.a.h.		
							Backshore: n.s.			*Backshore*: HEn 1=LEn< HEn 2		

continue

Note of Table 3.3:

[1] Denominator of *F vs.B*, *Beaches* and *Beaches x F vs.B*

[2] Denominator of Stations(*Beaches x F vs.B*)

[3] Data from HEn 1 was not available. Tested for differences between HEn 2 and LEn, only.

* P<0.05, ** P<0.01, *** P<0.001

n.s.=not significant

n.a.h.=no alternative hypothesis

3.4 Discussion

Deposition dynamics in sediment trapping in banquettes

Differences between banquettes morphology and rhizome biomass in high and low energy beaches, as well as differences in sediment concentration between foreshore and backshore can be explained in terms of banquettes deposition dynamics.

Vegetation litter deposition is strictly related to wave action. Mateo et al., (2003) proposed a theoretical sequence of formation and destruction of banquettes, involving an initial stage of litter deposition, with subsequent banquettes accretion (gain in size) up to the maximum height. After banquettes deposition, erosion by wave action occurs at the base, forming a scarp up to the collapse of the banquettes. The same authors reported that maximum dimensions are reached during winter, following severe storm conditions (Mateo et al., 2003). Vegetation litter on high energy beaches is often present in patterns which are representative of individual swash uprushes (Jackson et al., 2002).

We suggest that wave action could lead to the deposition of litter and sediments starting from the swash uprush line when the wave energy begins to decrease. The landward limit of banquettes marks the maximum wave run-up and banquettes deposition occurs seaward following the run-up decrease.

Landward, heavier material, rhizomes and sediments, are deposited leading to higher sediment concentration and rhizome biomass on the backshore (82.2 ± 55.7 kg m^{-3} and 0.15 ± 0.07 kg kg^{-1} respectively) in comparison with the foreshore (20.3 ± 21.9 kg m^{-3} and 0.05 ± 0.02 kg kg^{-1} respectively). When wave run-up decreases, many leaves are deposited and consequently sediment concentration on the foreshore is lower in comparison with the backshore.

Rhizomes were found only on high energy beaches. Rhizome uprooting requires heavy storm conditions (Preen et al., 1995). Consequently, rhizome uprooting from meadows adjacent to low energy beaches is lower, and lower rhizome biomass in banquettes of low energy beaches occurs.

During the autumn and winter, after leaves fall, the deposition of rhizomes, on high energy beaches, mark the maximum wave run up. After leaves fall, several erosion/deposition cycles could occur. In the spring-summer period (before leaves fall) rhizome content does not show significant differences between the backshore and foreshore. The rhizome deposition pattern before the leaves fall could be due to complex depositional cycles with partial banquettes erosion, winnowing and deposition at different levels reached by wave run-up.

Sediment concentration is independent of beach energy, while high and low energy beaches differ in banquettes volume. The banquettes depositional dynamics are similar on low and high energy beaches, leading in both cases to a higher sediment concentration on the backshore than on the foreshore. The development of wider and thicker banquettes on high energy beaches is due to the wider swash zone. This seems to be in contrast with the observation reported by Jackson et al., (2002), who highlighted that vegetation litter is more prevalent on low energy beaches due to the large amounts of vegetation growing in sheltered waters. In our case, *P. oceanica* meadows are widespread in both high and low energy sectors (Figure 4.1a) and consequently litter is available for both high and low energy beaches. Differences in banquettes volumes are mainly due to the different wave energy conditions.

Impact of banquettes removal on the beach sedimentary budget

Banquettes removal is a common practice on Mediterranean beaches (Chapter 2) and the finding of this study can give indications on the impact of removal on the sedimentary budget of the Mediteranean beaches.

The amount of sediment trapped in banquettes depends on the volume and sediment concentration of the banquettes. By taking the mean banquettes volume and the mean sediment concentration into consideration we can estimate the total volume of sediment trapped in banquettes which range from 6 to 79 m^3. Based on this data, the removal of 1000 m^3 of banquettes involves the subtraction of 19-44 m^3 of sediments. Data collected in 2004, highlighted that the removal of banquettes volumes higher than 1000 m^3 occurred on 17 sandy Sardinian shores for a total length of ca. 73 km (De Falco et al., 2007). Removal is carried out mainly with heavy machines without grid systems, which allow for the removal of sediments at the base of banquettes. Furthermore banquettes removal is carried out every year and, in some cases, more than one time per year (Chapter 2).

Consequently, banquettes removal can lead to the removal of hundreds of cubic meters of sediments per beach over several years, and can substantially unbalance the sediment budget, especially for those beaches characterized by low sedimentary input. The impact on the sedimentary budget could be minimized by a removal, by hand, of the part of the banquettes where sediment concentration is lowest. In this method, those banquettes accumulated on the backshore would be left intact. Furthermore, a thick leaf strata should be left on the beach in order to avoid the removal of sediments underlying the banquettes.

3.5 Conclusion

- Banquettes deposition occurs during the final phases of a storm event, when wave energy decreases. The landward limit of banquettes marks the maximum wave run-up, where heavier materials are deposited and lead to a higher sediment concentration on the backshore. Sediment concentration in banquettes is independent of the beach energy. The development of wider and thicker banquettes on high energy beaches in comparison with the low energy beach is due to the wider swash zone.
- Banquettes removal can result in the subtraction of hundreds of cubic meters of sediment from a single beach over several years, and can substantially unbalance the sedimentary budget of a beach. This impact can be reduced by adopting methods which allow for the minimization of sediment subtraction.

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CHAPTER 4

Effect of *Posidonia oceanica* banquettes on beach backshore morphology

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To be submitted

Abstract
This study investigates the variability of the morphology of three beaches located in western coast of Sardinia (western Mediterranean), characterized by banquettes deposition, The beaches were mapped using 6 Real Time Kinematic Global Positioning System surveys.

Elevation data of ground surface including banquettes and sediment-banquettes interface have been collected. The morphological variability of both levels was evaluated in order to analyze the relationships between banquettes depositional dynamics and beach geomorphology within beaches characterized by different wave energy conditions (i.e. low vs. high energy beaches).

In high energy beaches the deposition dynamics of banquettes is strictly correlated to the beach dynamics. Banquettes concur with sediments to the morphological changes driven by beach dynamics processes and contribute to the berm formation.

In the low energy beach banquettes are deposited as a layer over a generally invariant sedimentary substrate and vegetation litter deposits itself concur to the beach geomorphology.

Banquettes removal from high energy beaches could significantly alter the processes which controls beach geomorphology, while the low energy beach is probably less sensitive to this kind of impact.

Keywords: seagrass, leaf litter, beach morphology, EOF

4.1 Introduction

Seagrass are highly productive ecosystems of coastal areas (Duarte 2002). Most of production, due to the aboveground compartment (i.e. leaves) becomes litter which can accumulate in adjacent shorelines (Walker at al 2001).

Jackson et al. (2002) stated that beach vegetation litter is generally more prevalent on low energy beaches in comparison with high energy beaches, due larger amounts of vegetation growing in sheltered waters and the enhanced trapping caused by the breaks in shoreline orientation. The same authors highlighted that beach litter plays a greater role in geomorphic evolution of low energy beaches under non-storm conditions. Vegetational detritus creates nonsystematic and highly localized zones of accretion and scour, in contrast to the rhythmic features that are more common on high energy beaches (Jackson et al., 2002).

The seagrass *Posidonia oceanica* (L) Delile is endemic of the Mediterranean sea and constitute the mainly widespread seagrass meadows of the basin (Pergent et al 1995). *P. oceanica* loses the leaves in early autumn (Mateo and Romero 1996, Romero et al 1992), and leaf litter deposits can be found along sandy shores of the Mediterranean coasts (De Falco et al 2003, Mateo et al 2003). Beach leaf litter are commonly denominated ‘banquettes’, following early descriptions given by Boudouresque and Meisneiz (1982).

The deposition dynamic of banquettes has been discussed in the chapter 3 (Simeone et al., submitted) where it has been highlighted that banquettes deposition occurs during the final phases of a storm event, when wave energy decreases. The landward limit of banquettes marks the maximum wave run-up. The development of wider and thicker banquettes in high energy beaches in comparison with the low energy beach is due to the wider swash zone (Simeone et al submitted).

Banquettes removal can affect beach geomorphology. Beaches of the Mediterranean sea are typically microtidal (Gomez-Pujol et al. 2007) and morphological changes are mainly related to storm events (Baxterretxea et al., 2004).

Despite a conservative role in the beach protection from erosion has been often attributed to banquettes (Mateo et al., 2003), very few studies analyze the relationships between banquettes and beach morphology. This issue is relevant in order to understand the impact of banquettes removal on beach geomorphology.

This study investigates the variability of the morphology of three beaches characterized by banquettes deposition during one year. The aim is to analyze the relationships between banquettes depositional dynamic and beach geomorphology within beaches characterized by different wave energy conditions (ie low vs. high energy beaches).

4.2 Regional setting

The study area is located in the western coast of Sardinia, western Mediterranean (39°.55 lat N; 8°.25 long E) (Figure 4.1). The coastal area is studded by rock formations, which range in age from Neogene to Recent, involving Miocene marl and limestone, eolian and marine sandstone, and Quaternary dune fields. The geological setting of the Sinis Peninsula includes a Neogene sequence of volcanic and marine sedimentary rocks overlaid by a Pliocene plateau basalts. The Palaeozoic granite basement outcrops on the island of Mal di Ventre and along the continental shelf, whereas Pliocene basalts outcrop on the continental shelf, on the Catalano island (Fais et al., 1996; Marini & Murru, 1977).

The shelf morphology in this sector is tectonically structured with rises and depressions controlled by direct faults (Fais et al., 1996). Two rises (Mesa de Foghe and Mesa de Maluentu Catalano) are separated by a depression NW-SE oriented (Badde Arenas depression) (Carboni et al., 1989). The rises are generally colonized by *Posidonia oceanica* on rocky substrate while the depression is characterized by unvegetated soft sediments (Figure 4.1a).

The inner shelf in the southern sector is characterised by the presence of a semi-enclosed bay, the Gulf of Oristano. The gulf has a surface of approx. 150 km^2, is bounded to the west by rocky capes, and has a mostly sandy shoreline along an alluvial plain with several marshes and lagoons.

Three beaches, all characterized by deposition of *Posidonia oceanica* banquettes (i.e. Is Arenas, Maimoni and Su Siccu) were chosen as case studies (Figure 4.1a).

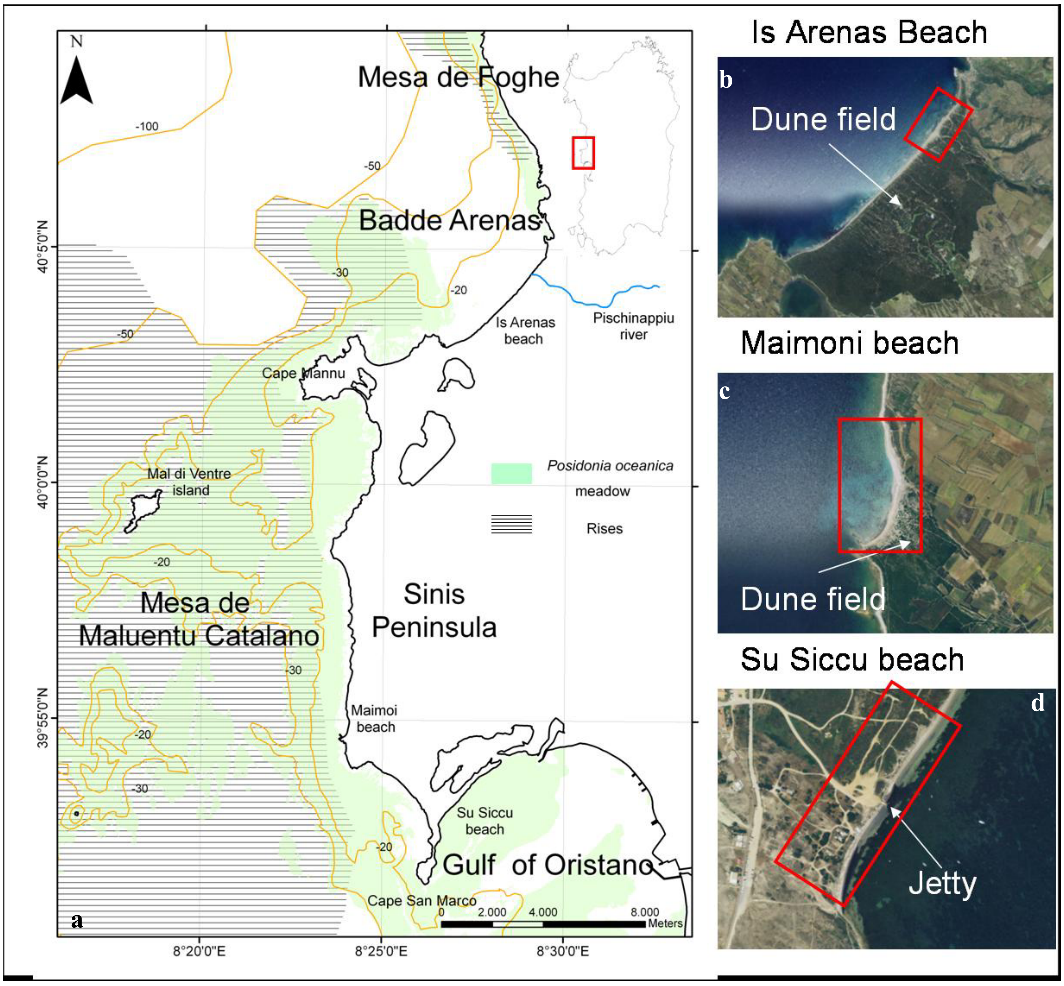

Figure 4.1: (a) Study site; (b) Is Arenas beach; (c) Maimoni beach and (d) Su Siccu beach.

Is Arenas beach is located in the northern sector and is the landward termination of the Badde Arenas depression. The total length of the beach is ca. 7.2 km, and an extended dune field (ca. 40 km^2) is present. The dunes have been immobilized in the late 50's by a forestation with pines. Beach sediments are constituted by medium sands (Simeone et al., submitted). A small seasonal river, the Pischinappiu river, inflows in the northern sector of the beach (Figure 4.1a). *Posidonia oceanica* meadows are present at north and south while are absent in front to the central sector of the beach. Banquettes are generally deposited between the river mouth and the rocky outcrop in the northern side of the beach (ca. 1 km), consequently this beach sector was chosen as study area (Figure 4.1b).

Maimoni beach is located in the Sinis Peninsula (Figure 4.1a). The seabed in this sector is characterized by rocky outcrop, sediment and *Posidonia oceanica* meadows with a matte, 50 cm thick, on rocky substrate. Maimoni beach is ca. 1.5 km length, sediments are typically bimodal composed by coarser siliciclastic grains mixed with finer biogenic particles (De Falco et al, 2003). Terrigenous sediment inflow is absent in this sector, while biogenic sediments derives from the transport from the *Posidonia oceanica* meadows (De Falco et al., 2003). An extended dune field is present in the southern sector of the beach (Figure 4.1c). Banquettes are usually deposited in the central sector of the beach (ca. 1 km) which was chosen as study sector.

Su Siccu beach is located inside the Gulf of Oristano (Figure 4.1a). The sea-bed is mainly constituted by sandy sediment colonized by *Posidonia oceanica* (De Falco et al 2008, Tigny et al., 2007). Beach sediments are mainly biogenic and constituted by medium-fine sands (Simeone et al., submitted). Banquettes occurs in the southern sector (ca. 400 m), where a little jetty is present (Figure 4.1d), which was chosen as study sector.

Mistral wind (i.e. north west) represents the dominant wind during all the year (Pinna, 1989) in western coast of Sardinia and the dominant direction of waves is 305° North degrees (Atzeni et al 2003). As reported by Atzeni et al. (2004), those beaches are characterized by the following mean annual energy of wave motion: Is Areans 138 GNm m^{-1}, Maimoni 118 GNm m^{-1} and Su Siccu 1 GNm m^{-1}. Following the values of the mean annual energy of wave motion Is Arenas and Maimoni can be considered as high energy beaches (hereafter called HEn1 and HEn2) while Su Siccu can be considered as a low energy beach (hereafter called LEn).

4.3 Material and methods

Data collection

Five topographic survey (March 2005, May 2005, August 2005, November 2005 and February 2006) were carried out for each investigated beach sector. For HEn2 beach one additional topographic survey was conducted in April 2005. For each beach the sampling area was comprised between the foredune foot and the foreshore scarp.

Ground elevation data were collected by using a Real Time Kinematic (RTK) - Differential Global Positioning System (DGPS) (Morton et al., 1993; Dail et al., 1999; Haxel and Holman, 2004). DGPS method ensures good accuracy in measuring the vertical position (<7 cm) as well as the horizontal position (<5 cm). Data have been collected by using a little vehicle that supports the antenna of DGPS with a known height from the ground. Due to the light weight and to the wideness of the wheels, the vehicle has a small footprint and the error in elevation is negligible. Data of position (X,Y and Z) were acquired in Real Time Kinematic (RTK) modality along a series of transects about 5 meters spaced, normal and parallel to the shoreline. RTK allows to collect the position (X,Y and Z) of a single point per second.

Elevation data of the sediment-banquettes interface were collected by using the Stop and Go modality (Morton et al., 1993), which allow to acquire the position of a single point. The elevation of sediment-banquettes interface was acquired in different points along a series of transect normal and parallel to shoreline, 5 meters spaced. The distance between two contiguous points was, for each transect was ca. 2 meters. The elevation of sediment-banquettes interface was determined by subtracting the banquettes thickness from the ground elevation acquired by Stop and Go modality.

A manual penetrometer was used in order to measure the thickness of banquettes. The penetrometer is constituted by a steel penetration pole 2.5 meter long (Figure 4.2). A cylindrical weight (1 kg) has been left to fall from the top of the pole up to the welded stop, running along the pole for 0.5 m. As consequence the pole penetrates into the substrate. The penetration depth is related to the substrate compactness. The penetrometer was calibrated before data collection. The penetration depth for the banquettes, for each run of the weight, is ca 20 cm in average, for the first layers of banquettes, and ranging between 5 and 10 cm for the deeper layers. The penetration depth for the unconsolidated sand in the investigated beaches was in the range between 1.5 ÷ 2.5 cm for each run of the weight.

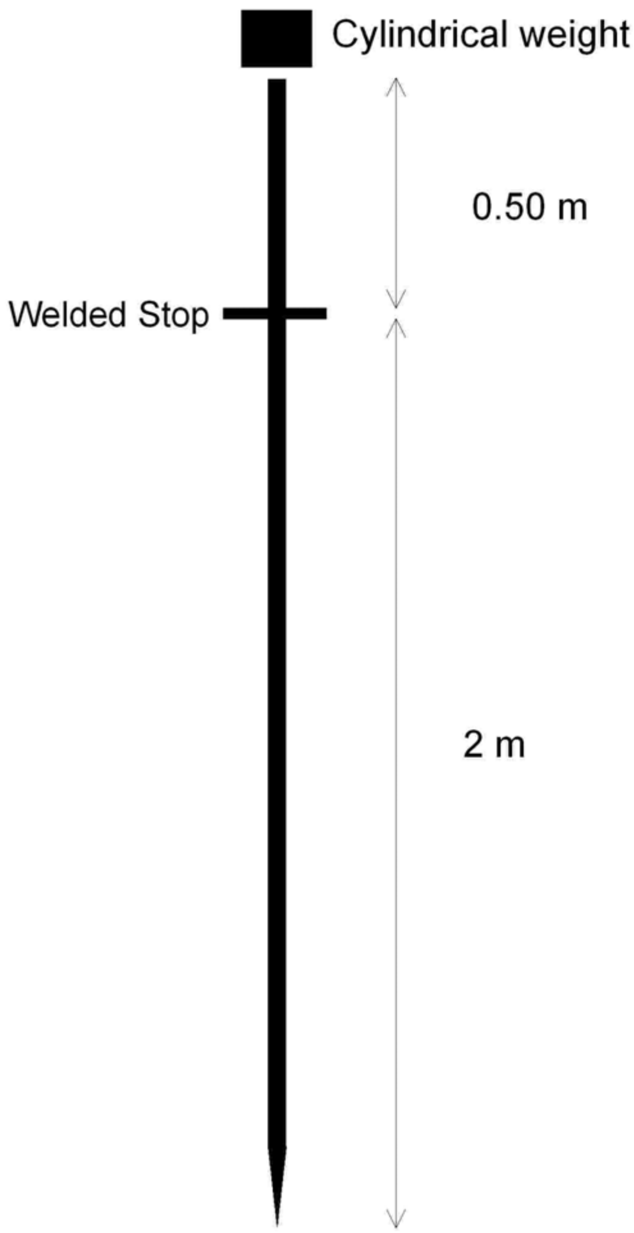

Figure 4.2: scheme of penetrometer

Data Processing

Data obtained from the field activities were interpolated by using SURFER software (Golden Software ®). Natural neighbouring gridding procedure was used to obtain two grids: (i) the ground elevation surface and (ii) the sediment-banquettes interface surface. The first grid represents the topographic level of the ground (hereafter called banquettes grid) while the second grid represents the elevation of the sediment-banquettes interface (hereafter called sediment grid) (Figure 4.3a).

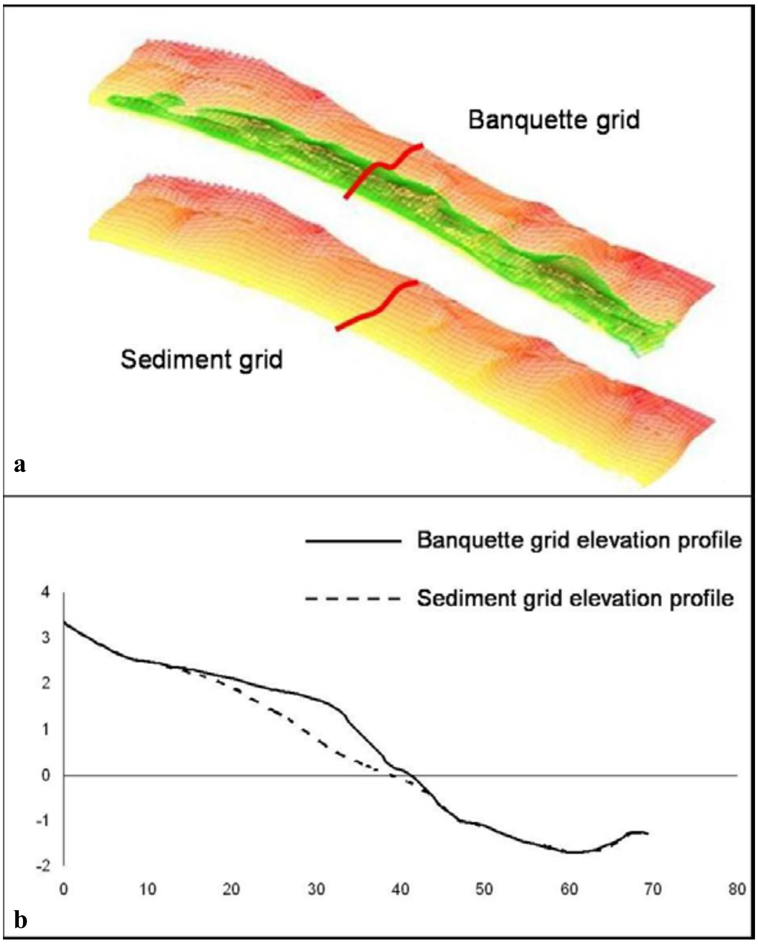

Figure 4.3: (a) Banquettes and sediment grid; (b) banquettes and sediment grid elevation profile

Banquettes volume was also calculated. The Volume tool of the interpolation software allows to compute the volume between the two grids, equivalent to banquettes volume. For each interpolation procedure the same limits of grids and the same grids spacing were used.

Beach profiles were obtained from the sediment grids and from the banquettes grids by using the Slice tool of the SURFER software (Figure 4.3b).

The mean and standard deviation of elevation between each campaign were calculated for each grid point and plotted as contour maps. The standard deviation allows to identify the sectors of higher variability of elevation surfaces.

In order to detect the main patterns of variability of the elevation data acquired by DGPS, Empirical Orthogonal Functions (EOFs) was performed (Haxel and Holman, 2004; Komar, 1998). The modes of spatial variability, also known as EOFs (EOF1, EOF-2,... EOF-n), contain information about the variability of the data, not necessarily related to physical features. For this reason the interpretation of the EOFs mainly aims to relate the data modes to physical phenomena. A percentage of variance is associated at each EOF. All the data obtained from gridding operation have been pre – processed in order to perform the EOFs analysis. In particular the matrices (XY) containing the gridded elevation data have been vectorized in a vector with dimension $p = X * Y$.

A matrix F with dimension $n*p$ does obtained for each relief; n is the number of observation (5 or 6) and p is the number of grid point (samples) for each observation. We can consider each of the p column of matrix F as a time series for a given location xy, and each of the n row as an observation (single field) for a given time t.

The EOF analysis is then performed on the data organized in such F matrix. The resultant EOFs, in form of vectors, are then re-converted in matrices before drawing the EOF maps.

4.4 Results

Banquettes deposition and beach morphology

The banquettes thickness for each beach is reported in figure 4.4, while the mean volume of banquettes for each beach has been reported in table 4.1.

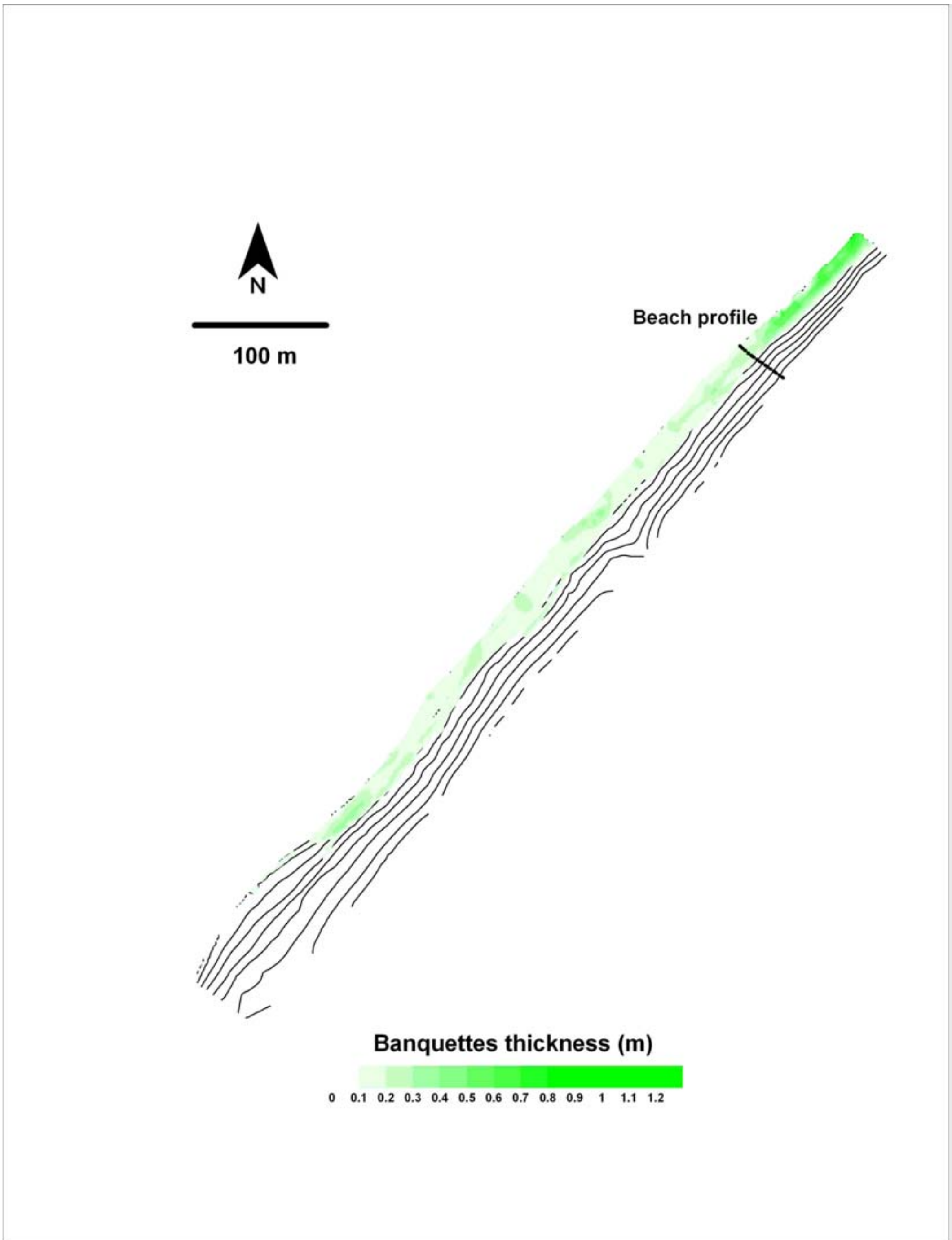

Figure 4.4a: banquettes thickness in HEn 1beach

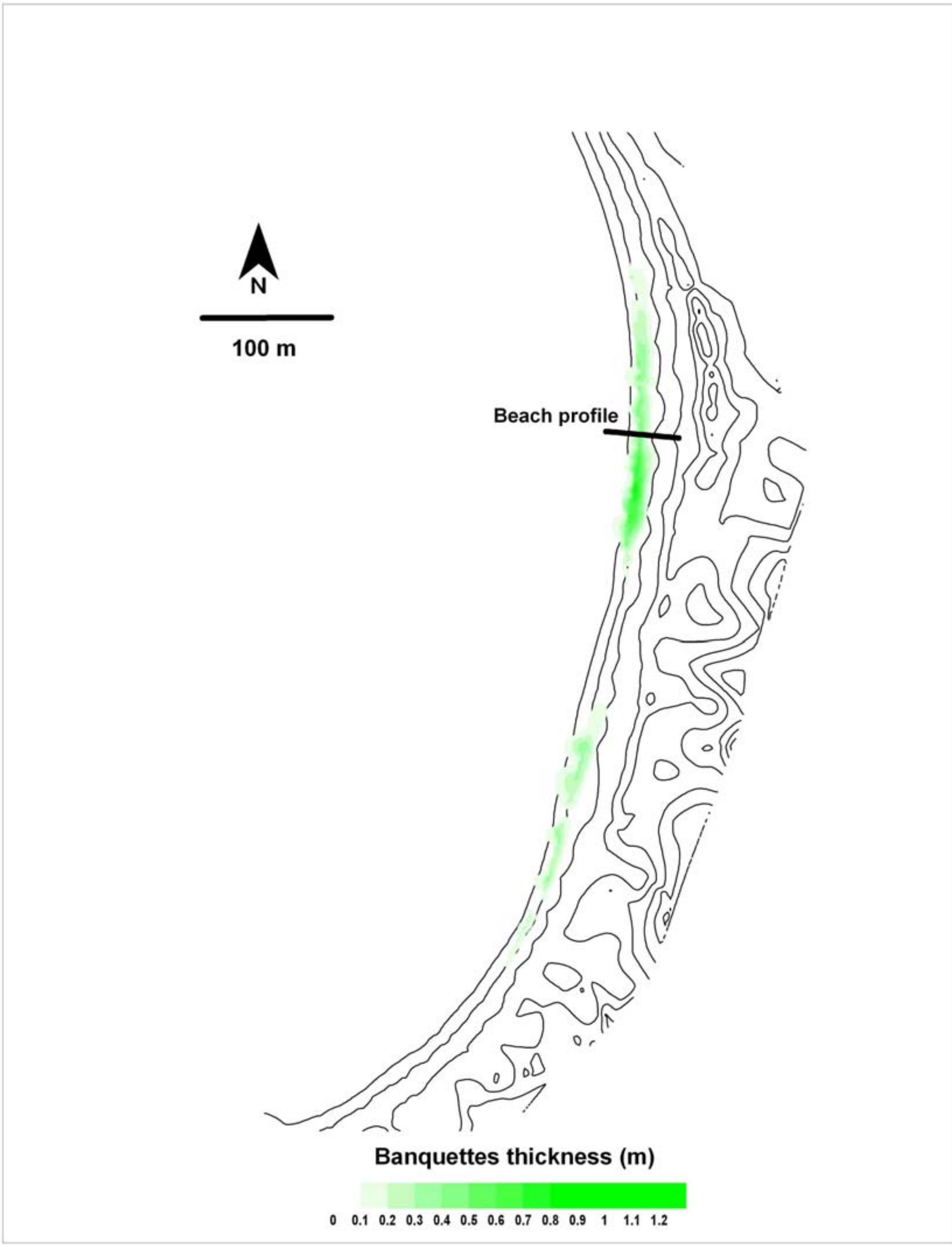

Figure 4.4b: banquettes thickness in HEn 1beach

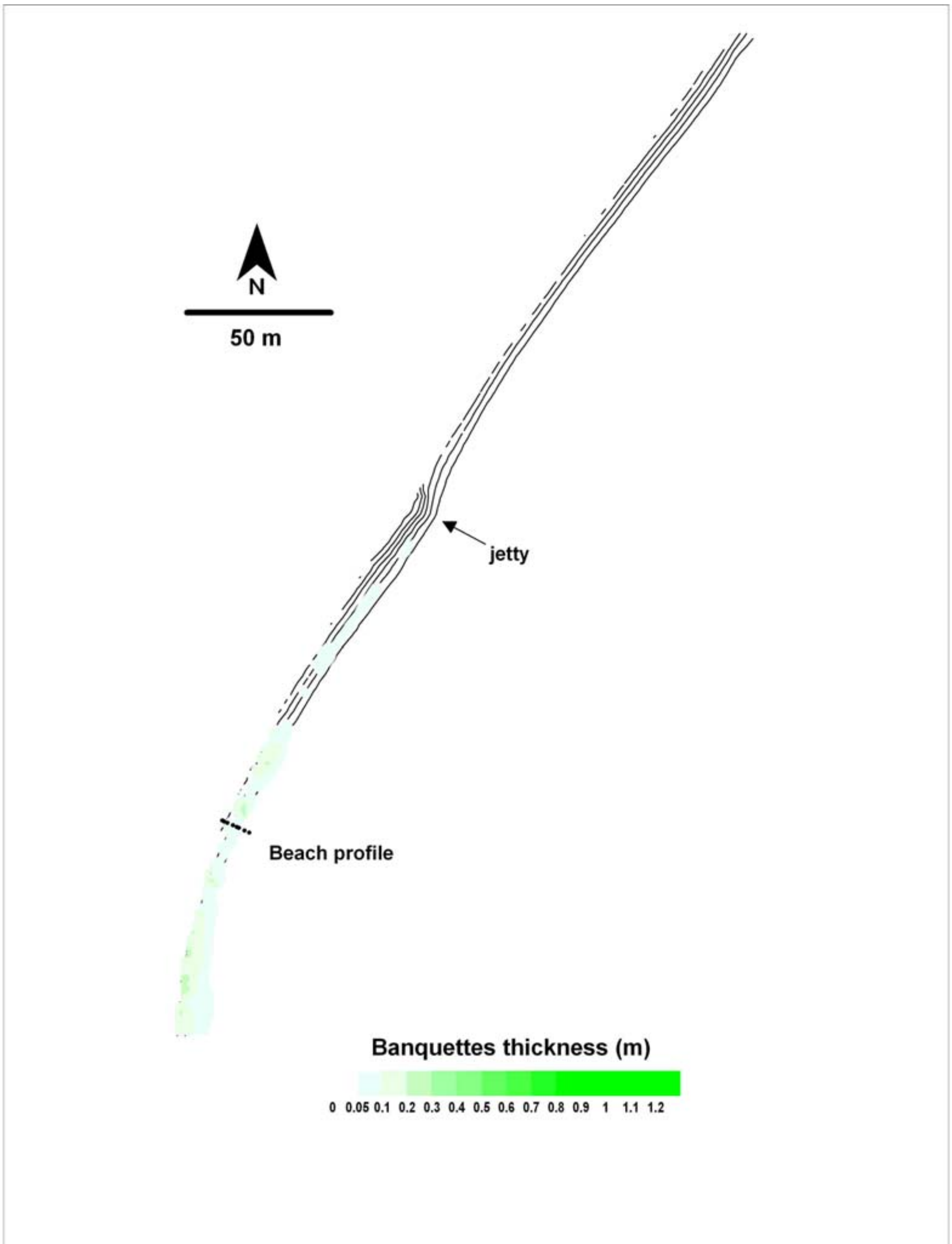

Figure 4.4c: banquettes thickness in LEn beach

Difference in banquettes thickness and volumes have been found between high and low energy beaches. High energy beaches show a higher mean amount of banquettes deposed during the investigated period (3362 ± 3342 and 1889 ± 1566 m^3) with respect to low energy beach (154 ± 130 m^3). Differences were also found in the morphology of banquettes between high and the low energy beaches. Maximum banquettes thickness as well as the maximum width is found in HEn1 (1.57 ÷ 19 m) and in HEn2 (2.2 ÷ 22 m) with respect to LEn (0.4 ÷ 7 m).

Table 4.1: Descriptive statistics of banquettes volume on investigated beaches

		Beaches		
		HEn 1 (n=4)	**HEn 2** (n=5)	**LEn** (n=5)
Volume of Banquettes (m^3)	Mean ± S.D.	3362 ± 3342	1889 ± 1566	154 ± 130
	Range	1127 ÷ 8641	277 ÷ 4400	22 ÷ 365
Maximum width of banquettes (m)	Mean ± S.D.	14.5 ± 5.7	16.8 ± 3.4	5.4 ± 0.6
	Range	7.0 ÷ 19.0	13.0 ÷ 22.0	4,0 ÷ 10,0
Maximum thickness (m)	Mean ± S.D.	1.1 ± 0.7	1.4 ± 0.6	0,3 ± 0,1
	Range	0.9 ÷ 1,6	0,7 ÷ 2,2	0,2 ÷ 0,4

The mean morphology of the sediment banquettes interface, obtained from the sediment grids, shows differences between high and low energy beaches. In the former rhythmic forms occurred while in the latter they were absent.

In HEn1 beach three rhythmic shoreline forms, spaced hundreds of meters, have been recorded (Figure 4.5a), in HEn2 beach cusps with decreasing spacing from north to south (from 100 m up to 20 m) have been detected (Figure 4.5b). No morphological structure were found in LEn beach where a little jetty, located in the central part of the beach, modifies the straight shoreline (Figure 4.5c).

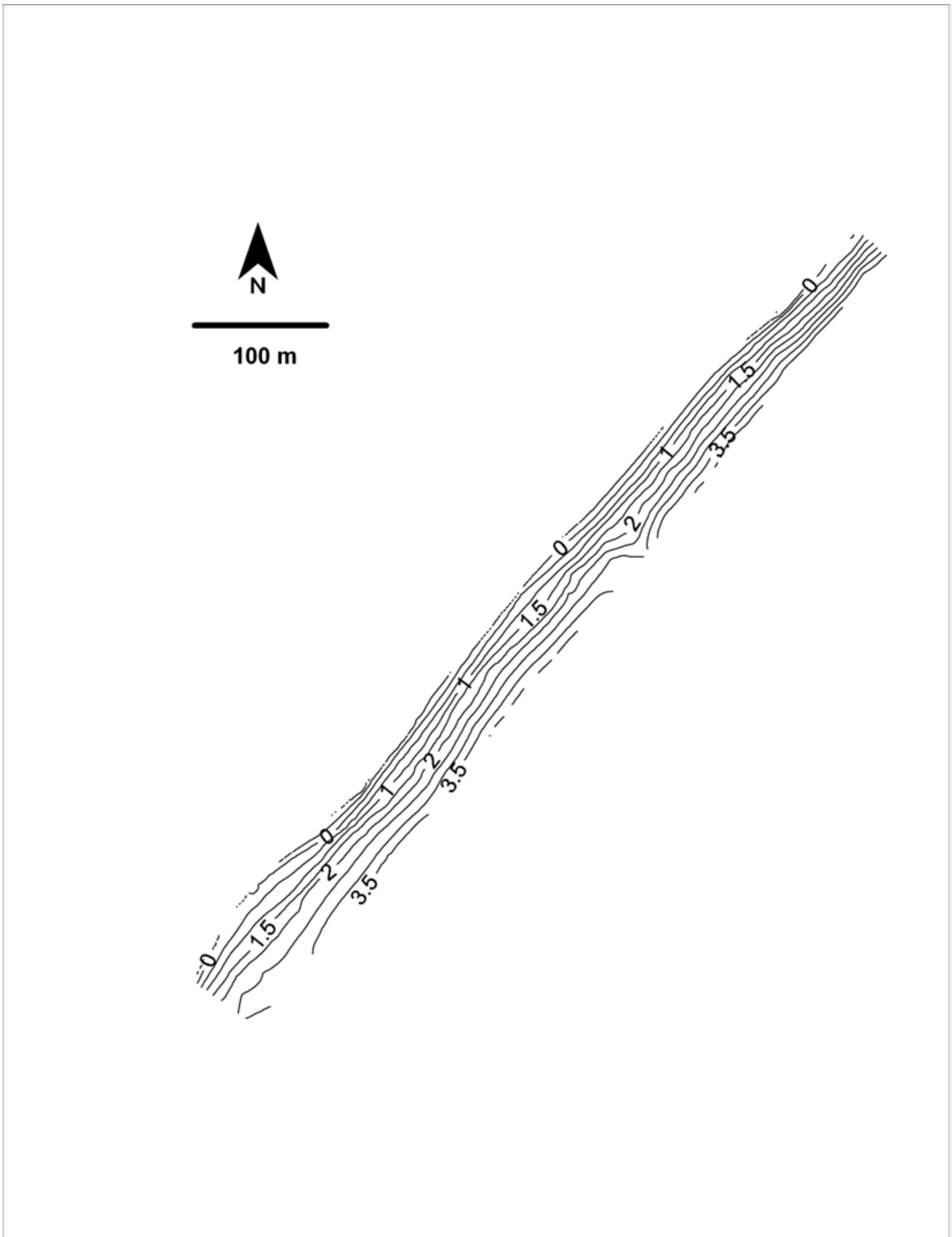

Figure 4.5a: mean elevation of sediment-banquettes interface in HEn1

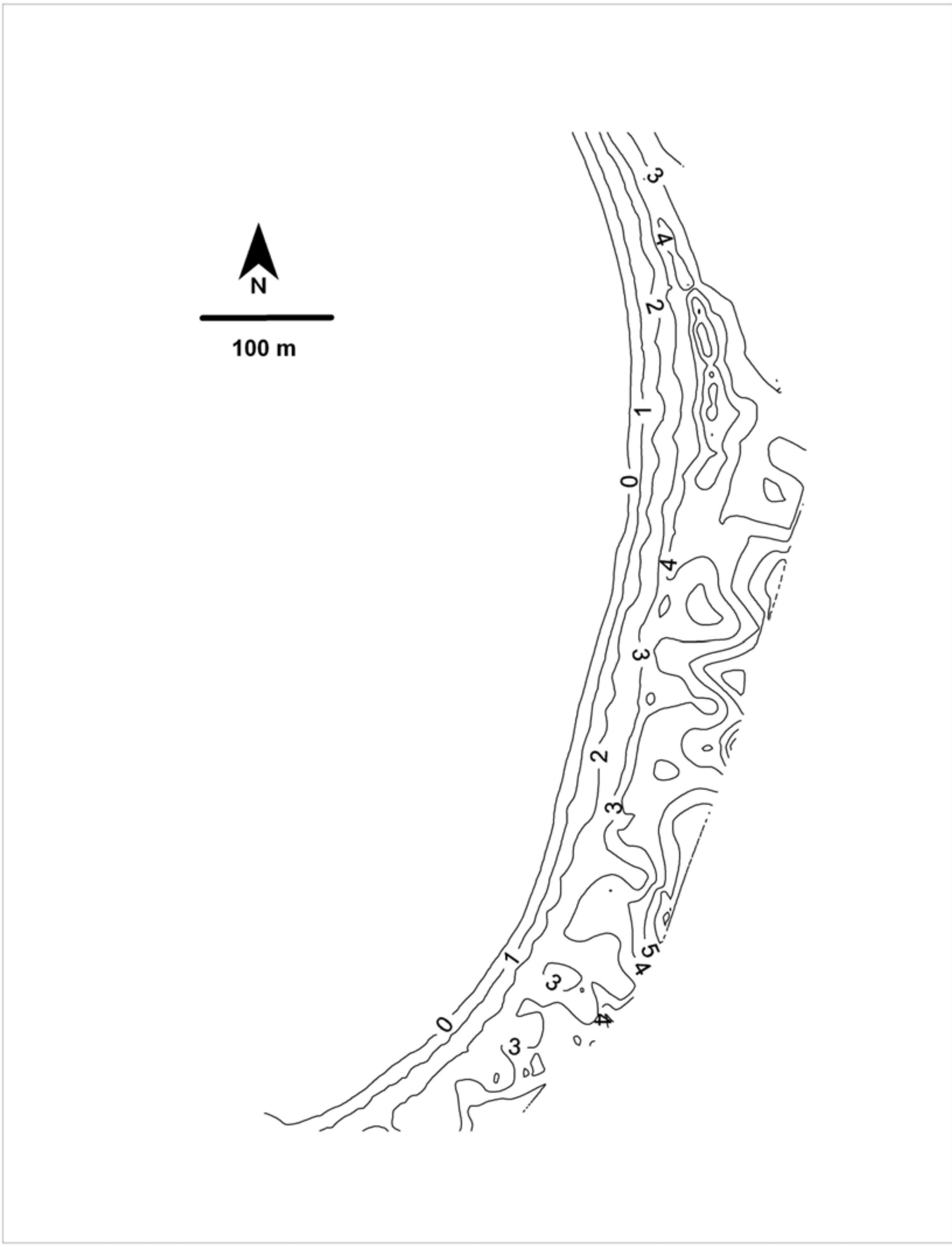

Figure 4.5b: mean elevation of sediment-banquettes interface in HEn2

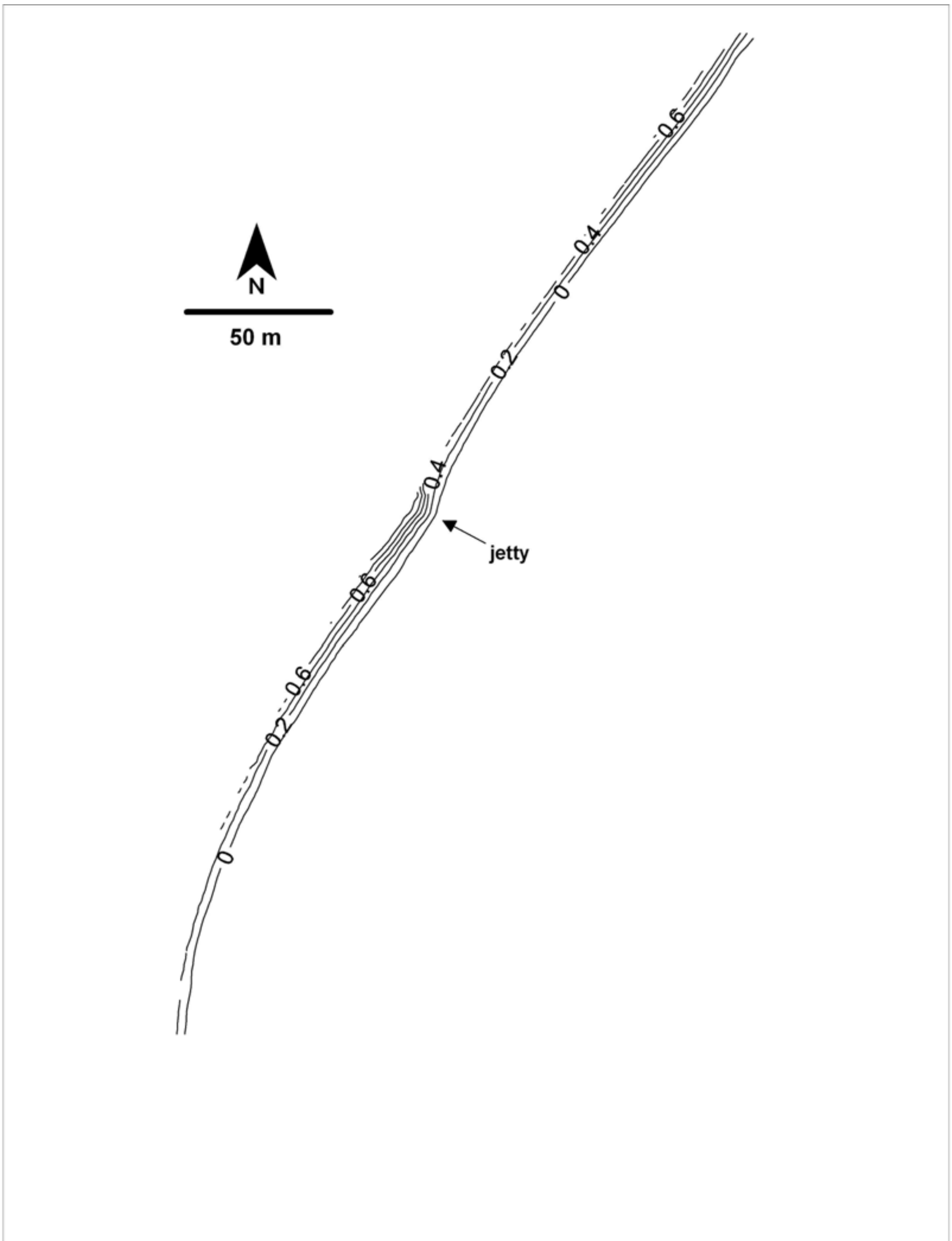

Figure 4.5c: mean elevation of sediment-banquettes interface in LEn2

Variability of beach morphology

The standard deviation of banquettes and sediment grids are reported in figures 4.6 and 4.7.

Figure 4.6a: spatial distribution of standard deviation of banquettes grids in HEn1

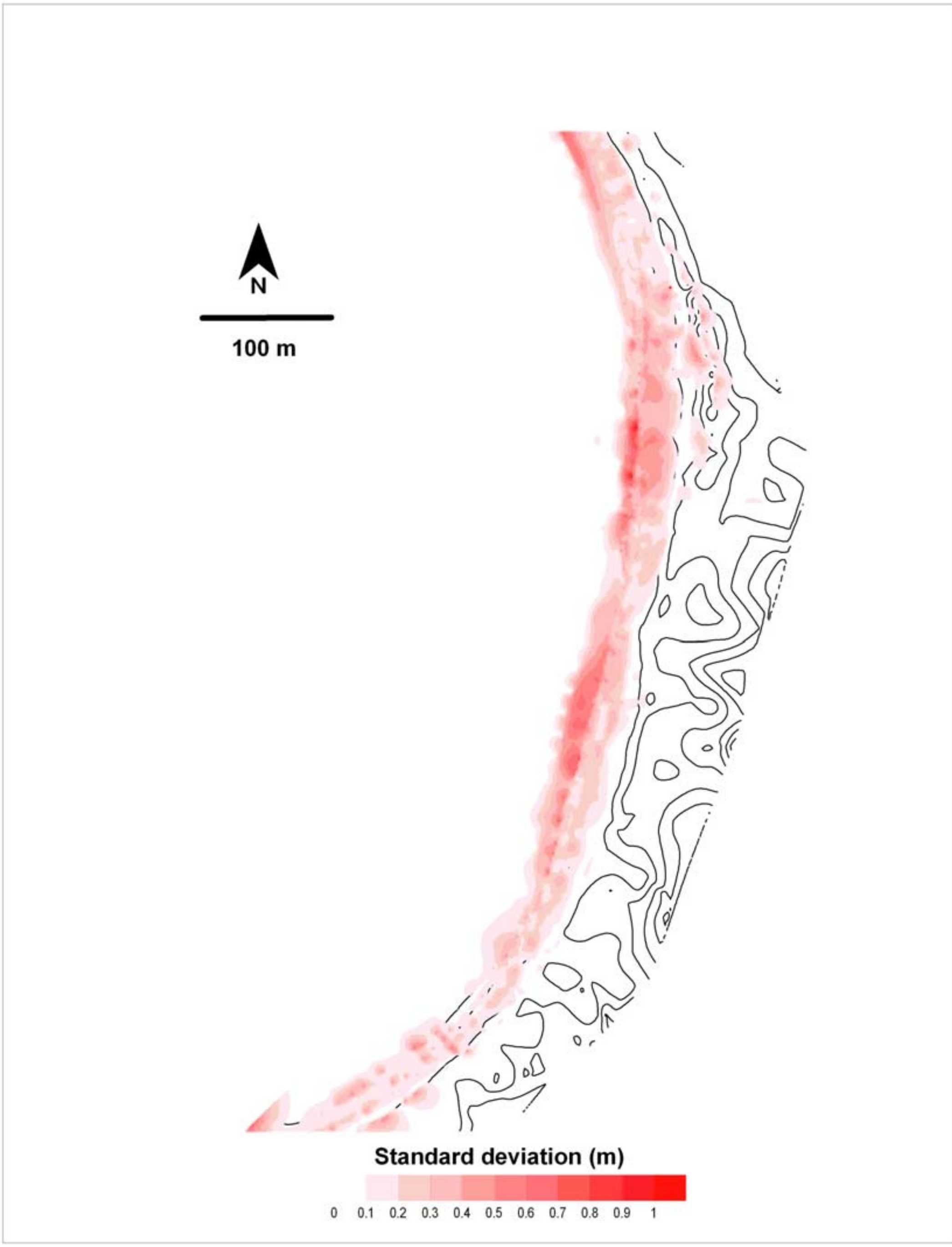

Figure 4.6b: spatial distribution of standard deviation of banquettes grids in HEn2

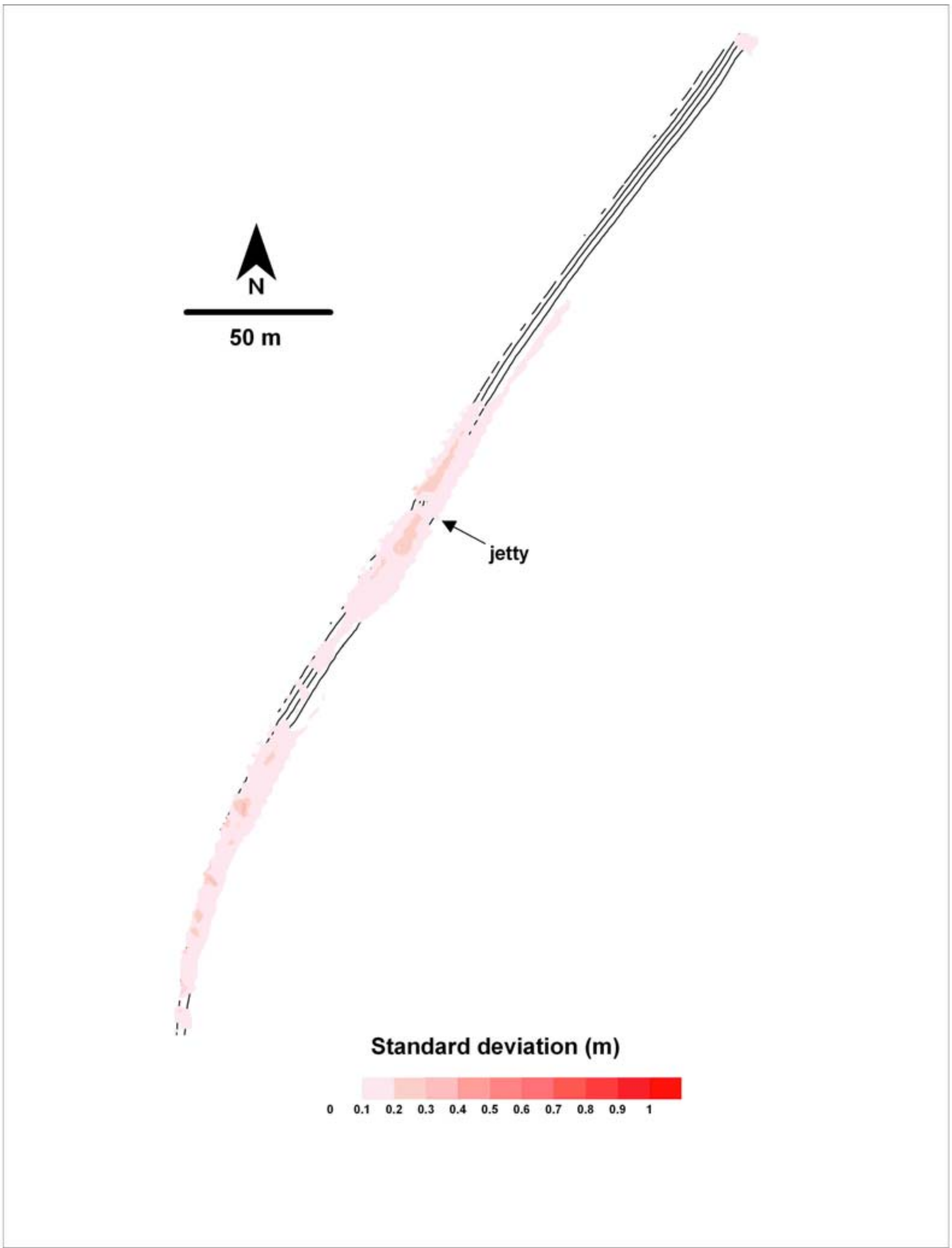

Figure 4.6c: spatial distribution of standard deviation of banquettes grids in LEn

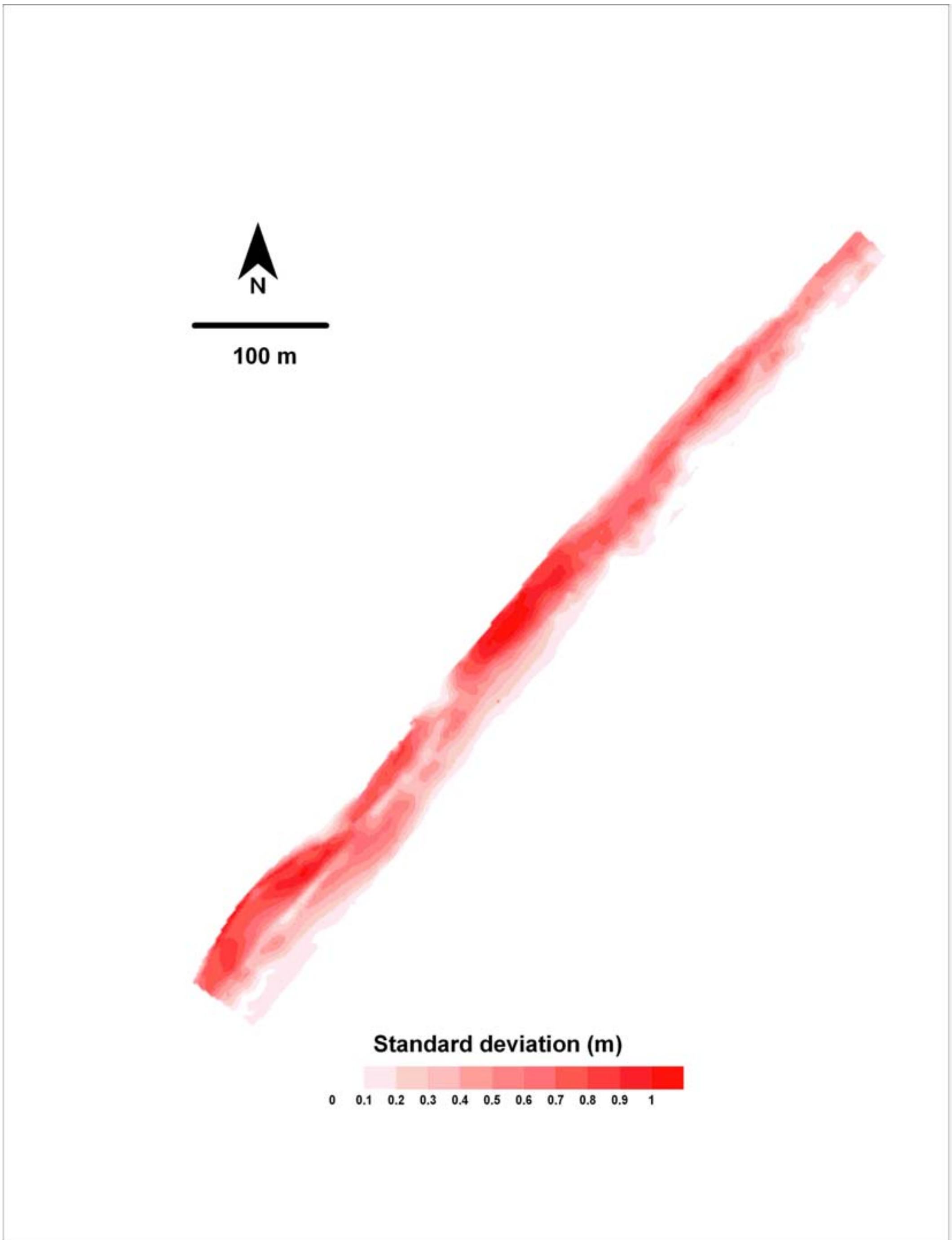

Figure 4.7a: spatial distribution of standard deviation of sediment grids in HEn1

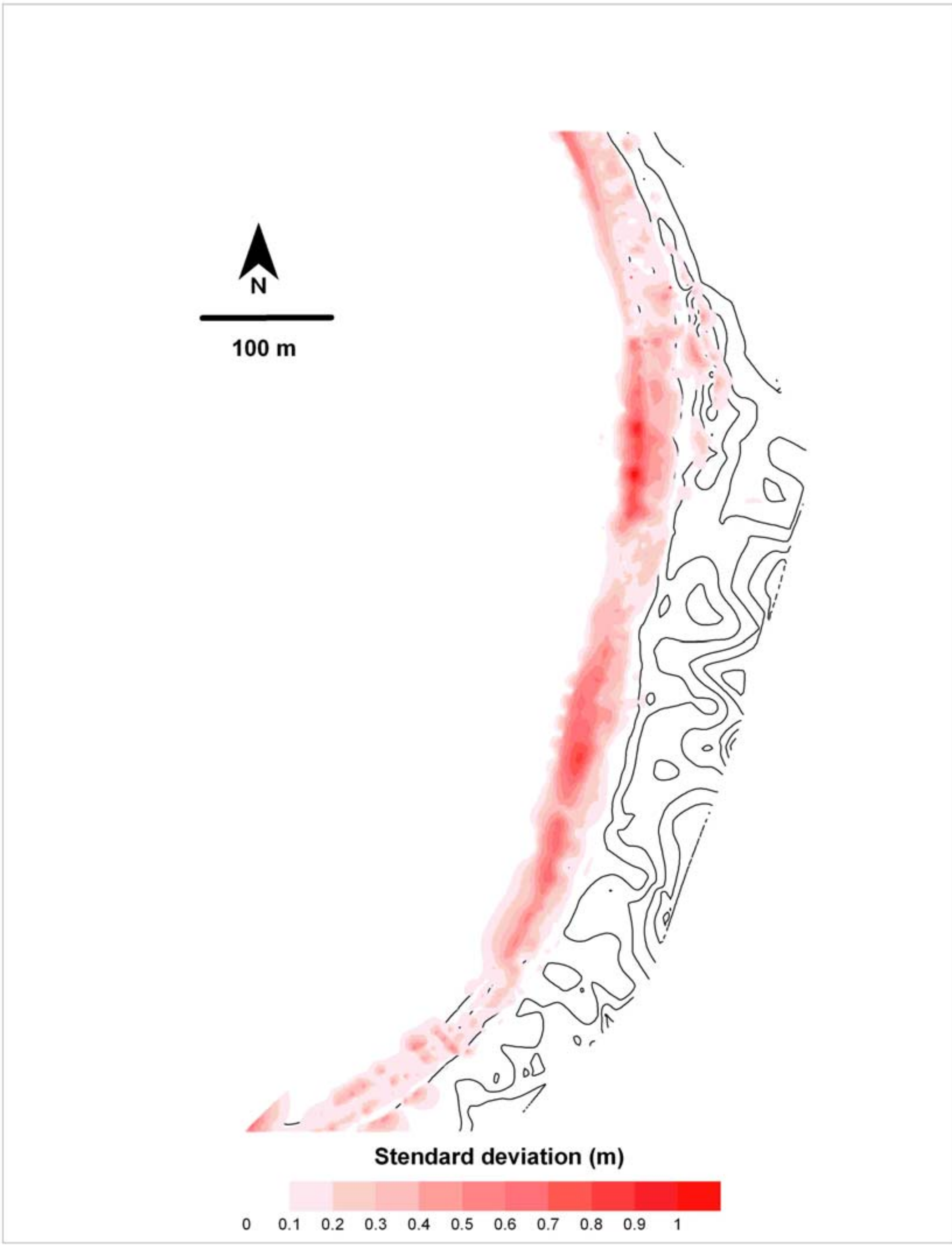

Figure 4.7b: spatial distribution of standard deviation of sediment grids in HEn2

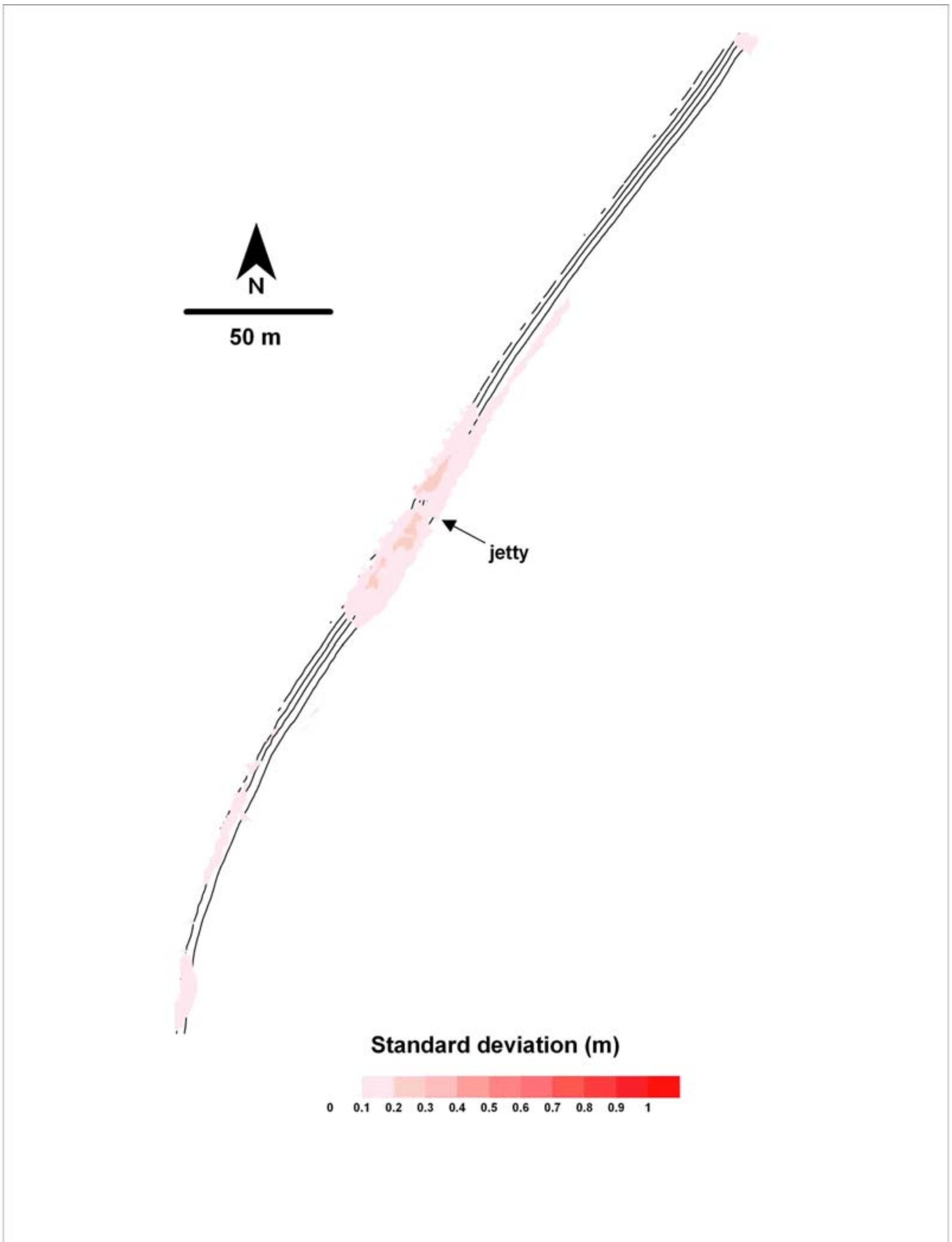

Figure 4.7c: spatial distribution of standard deviation of sediment grids in LEn

The high energy beaches show greater variability in comparison with the low energy beach. The maximum standard deviation of ground elevation data (banquettes grid) is ca. 1 m in HEn1 and HEn2 beach and 0.35 m in LEn beach. The same values can be detected for the standard deviations of banquettes-sediment interface elevation data (sediment grid).

The spatial distribution of standard deviation in HEn1 beach highlights three areas where greater variability occurs hundreds of meters spaced. In HEn2 beach the variability is localized in three sectors while in LEn beach the variability is localized mainly in correspondence of the jetty.

The differences of standard deviation between the two grids has been computed in order to evaluate the contribution to the variability of morphology due to sediment and banquettes dynamics (Figure 4.8). Positive values of the difference of standard deviation indicate that sediment grid is more variable than banquettes grid, while negative values indicate an opposite trend. In high energy beaches positive values are prevalent thus indicating greater variability of sediment grid (i.e. sediment-banquettes interface) in comparison to banquettes grid. In the low energy beach the difference between standard deviations is negative, thus indicating a grater variability of the banquettes grid.

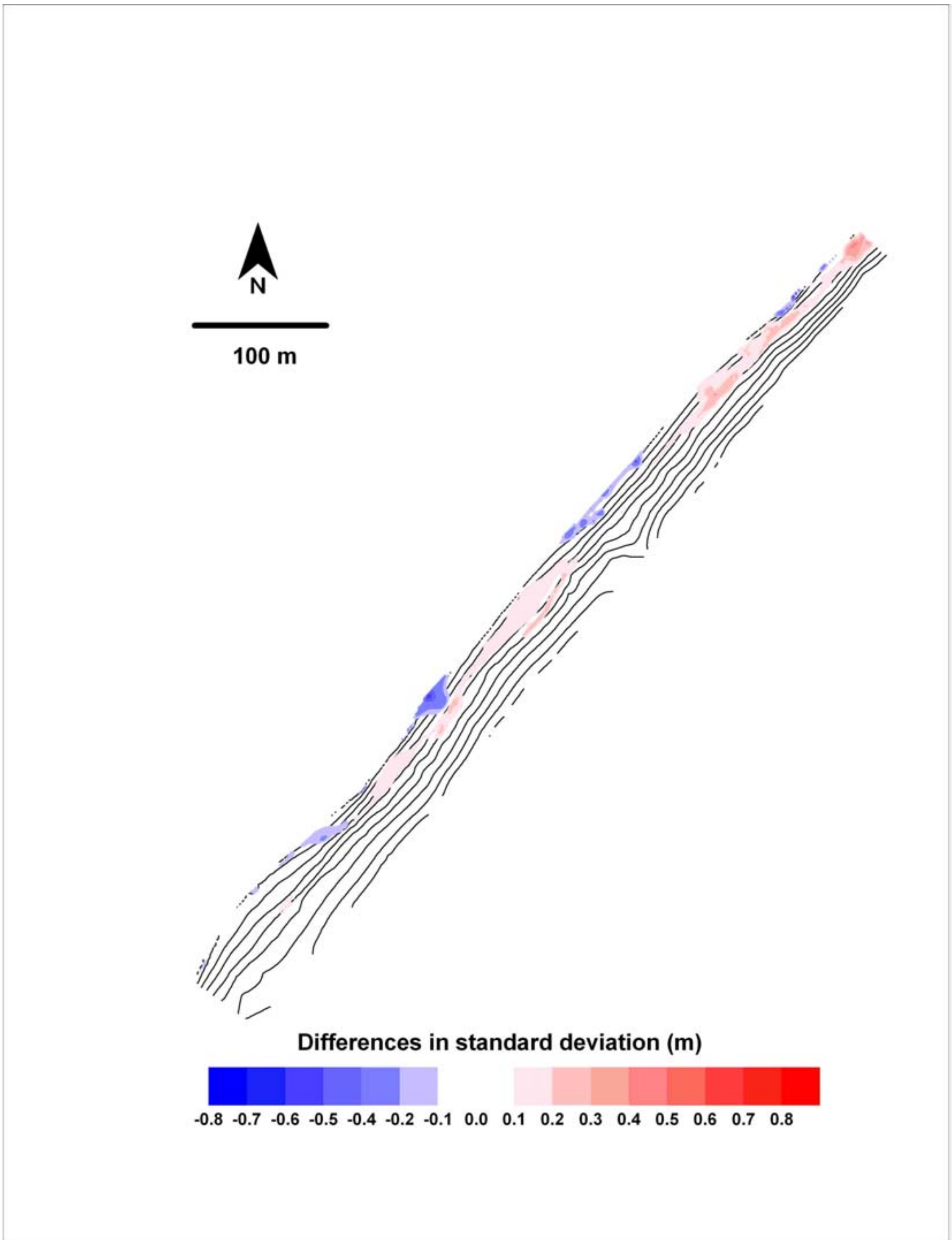

Figure 4.8a: difference of standard deviation between sediment and banquettes grids in HEn1

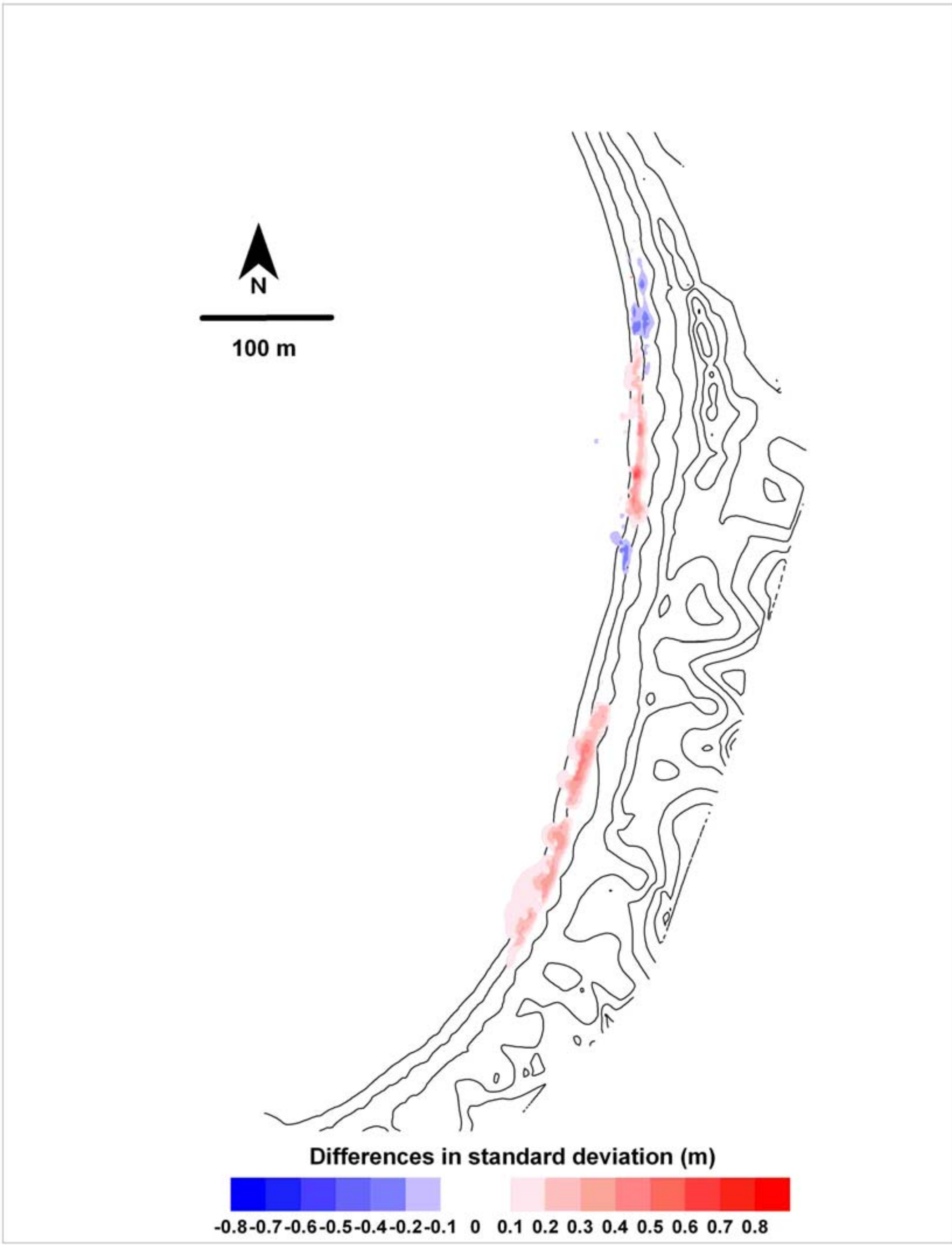

Figure 4.8b: difference of standard deviation between sediment and banquettes grids in HEn2

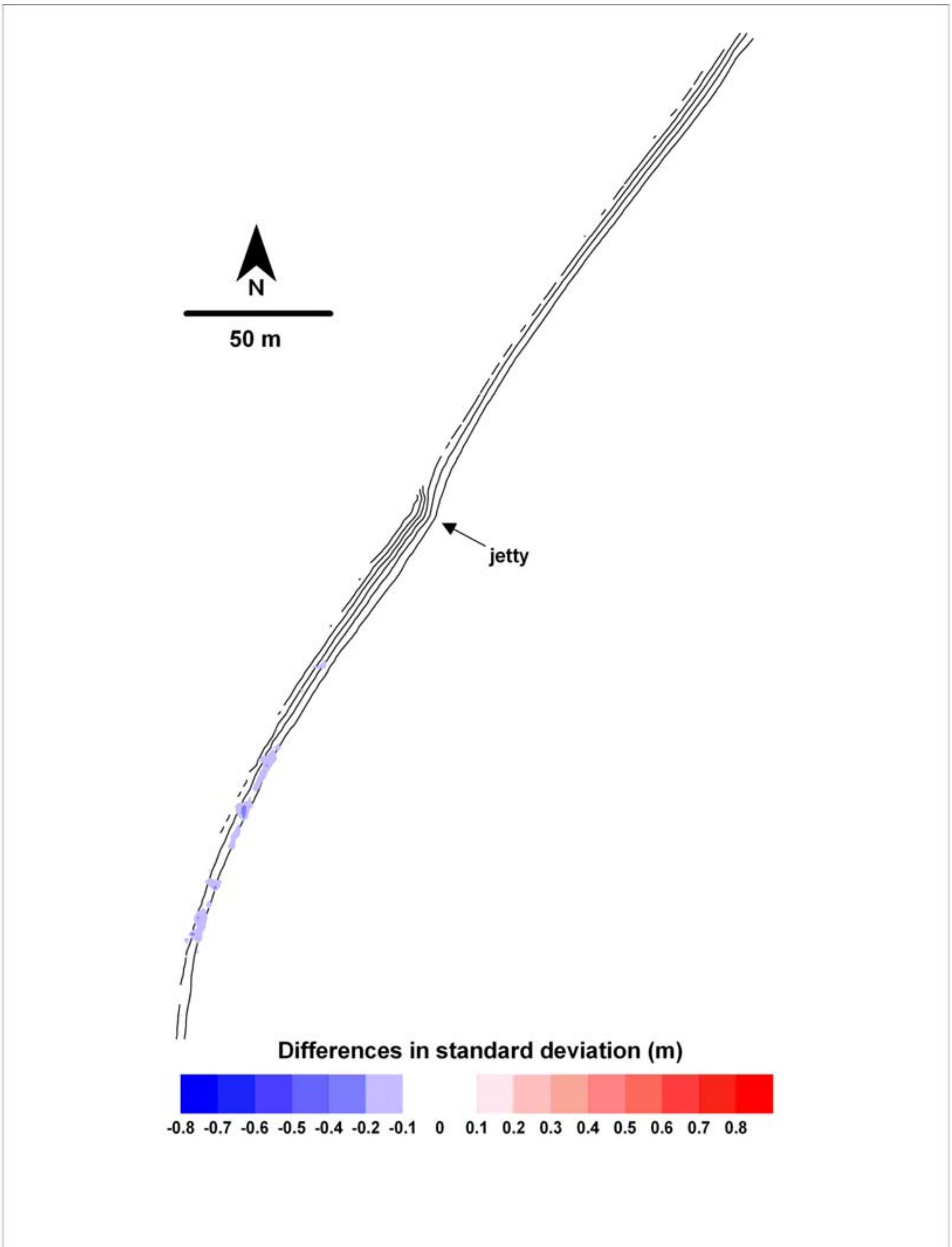

Figure 4.8c: difference of standard deviation between sediment and banquettes grids in LEn

EOF analysis was performed for both grids. Two modes have been extracted, the first mode have been considered to describe the main morphological changes (Dail et al 2000).

The spatial distribution of the first EOF's mode of banquettes grids are reported in figure 4.9. The explained variance is 59.40% for HEn1 beach, 63.75 % for HEn2 beach and 56.93% for LEn beach.

The spatial distribution of the first EOF in HEn1 identifies three areas of variability, two of them localized in the northern sector which are in opposition of phase with respect to the area localized in the southern sector (Figure 4.9a). In HEn2 beach the spatial distribution of the first EOF mode (Figure 4.9b) identify three areas of variability, two of them localized in the central sector which are in opposition of phase with respect to the area localized in the northern sector. Spatial distribution of first EOF in LEn beach shows that the variability is mainly localizes in correspondence of the jetty and in the sector of beach where the banquettes were usually found (Figure 4.9c).

The spatial distribution of the first EOF's mode of sediment grids are reported in figure 4.10. The explained variance is 59.34% for HEn1 beach, 65.30 % for HEn2 beach and 62.70% for LEn beach.

The pattern of variability of EOF's first mode for the sediment grid is similar to the previous described pattern of the banquettes grid for the high energy beaches. In the low energy beach the variability of sediment grid is only located in proximity of the jetty.

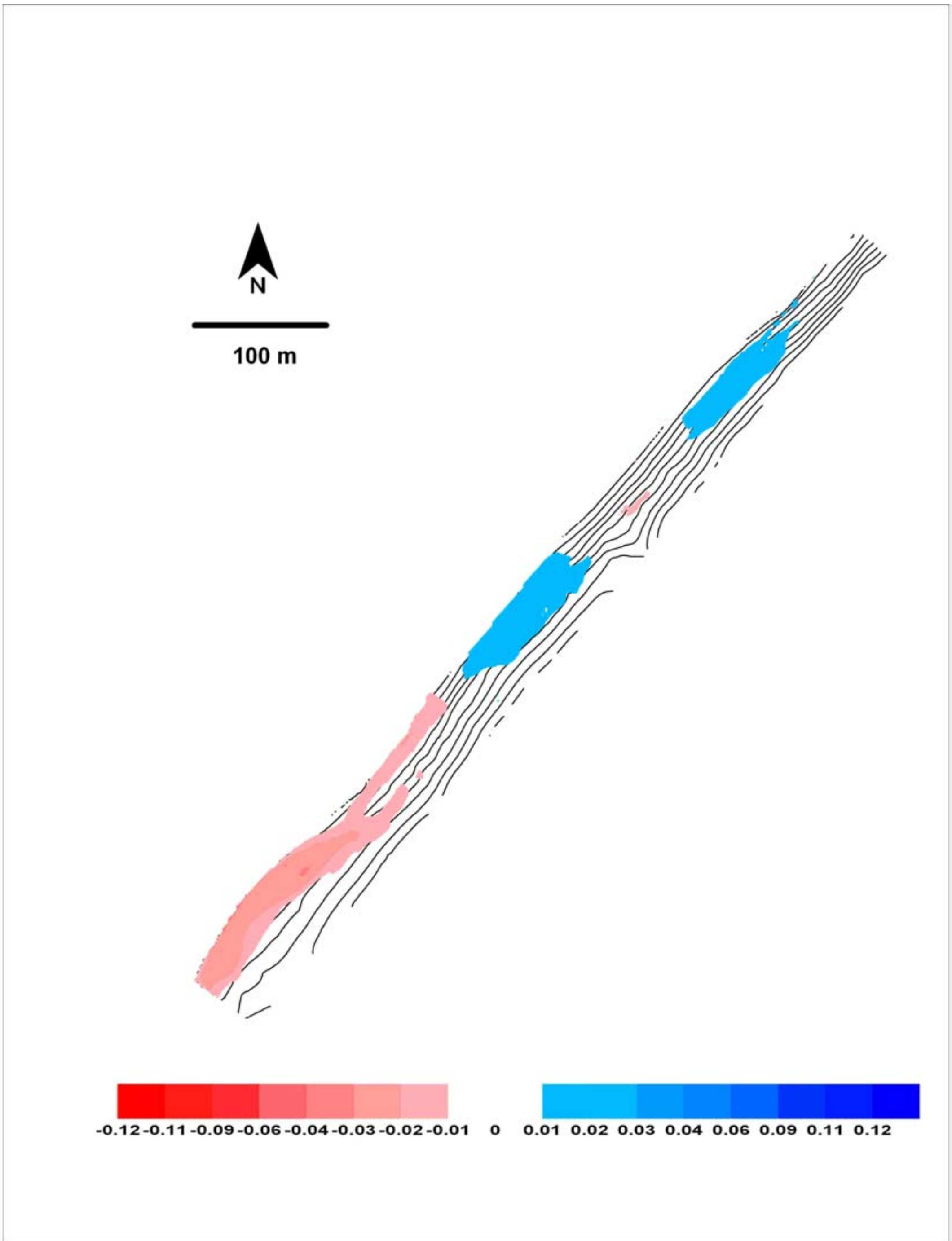

Figure 4.9a: spatial distribution of first EOF mode for banquettes grids in HEn1.

Figure 4.9b: spatial distribution of first EOF mode for banquettes grids in HEn2.

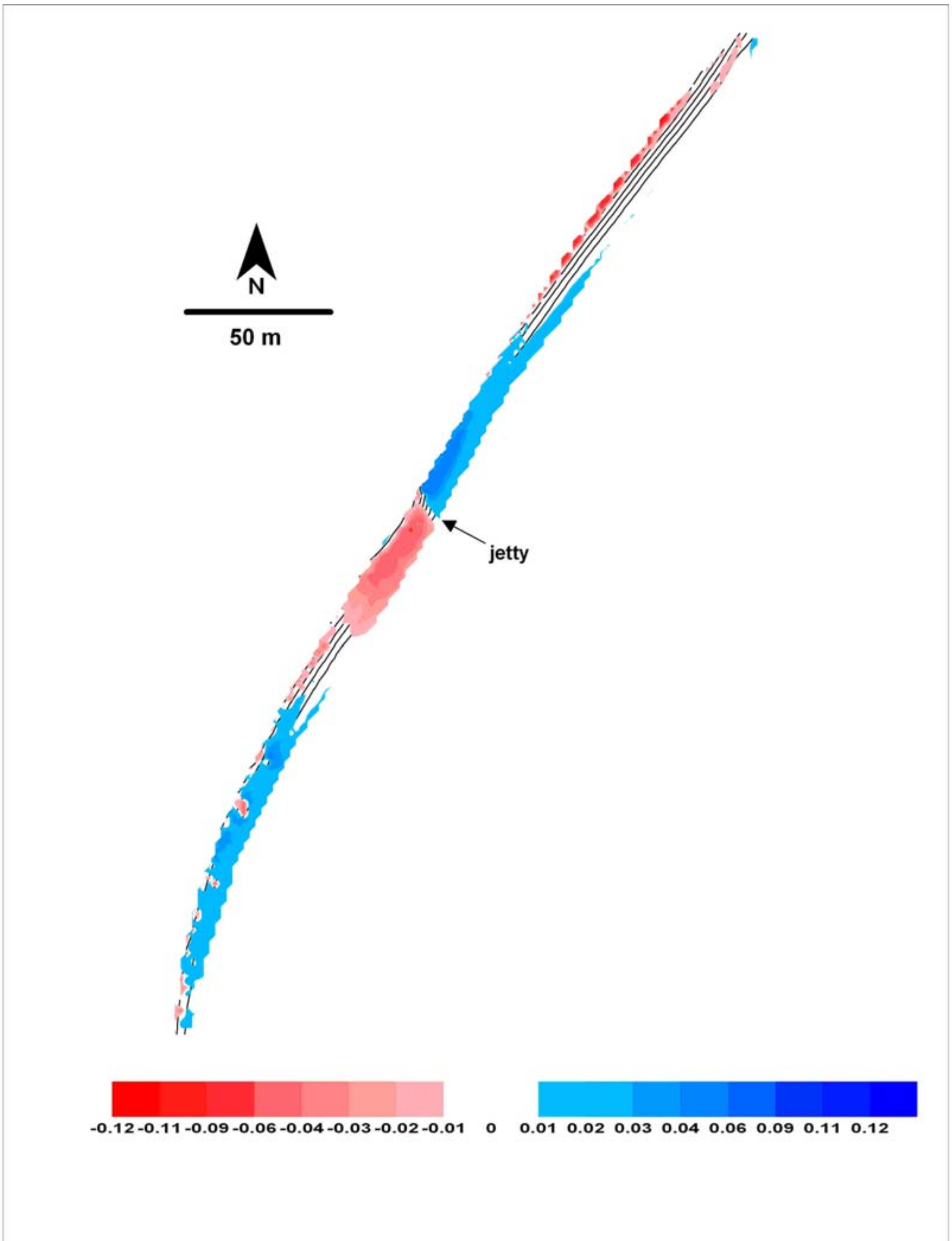

Figure 4.9c: spatial distribution of first EOF mode for banquettes grids in LEn.

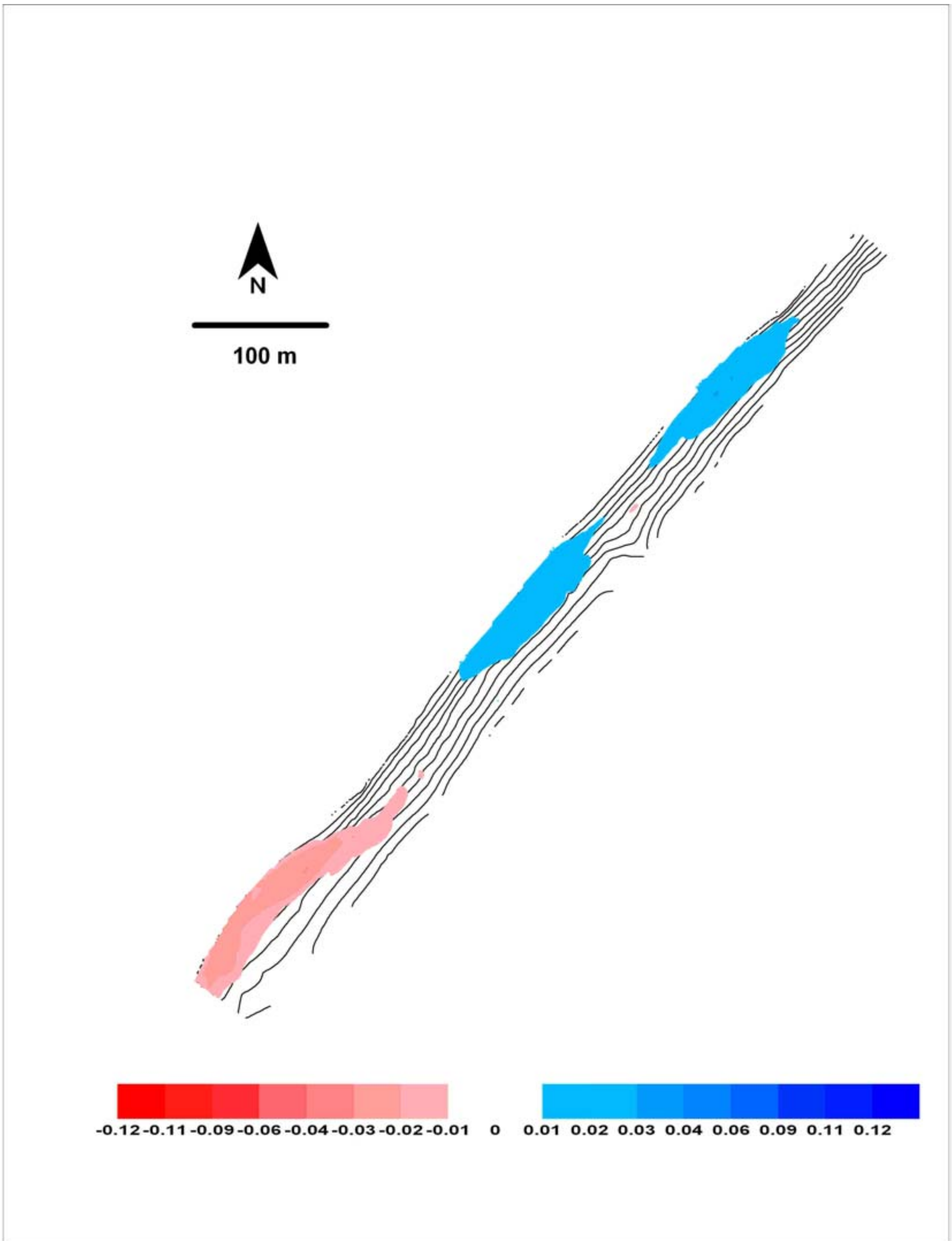

Figure 4.10a: spatial distribution of first EOF mode for sediment grids in HEn1.

Figure 4.10b: spatial distribution of first EOF mode for sediment grids in HEn2.

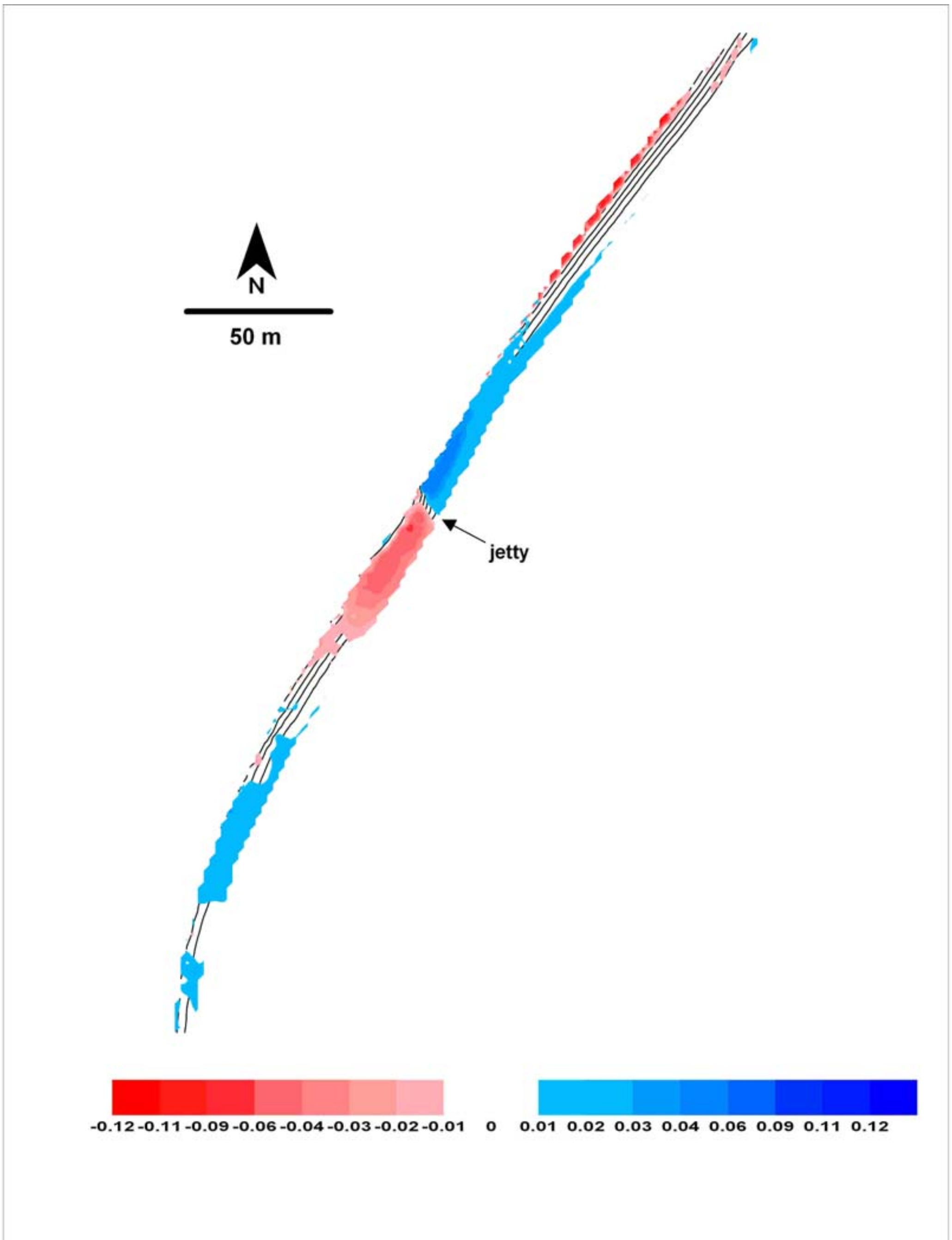

Figure 4.10c: spatial distribution of first EOF mode for sediment grids in LEn.

4.5 Discussion

In high energy beaches the deposition dynamics of banquettes is strictly related to the beach dynamics, while in the low energy beach banquettes are deposited over a generally invariant beach surface.

The analysis of morphological variability of high energy beaches shows the presence of morphological features developed longshore. Three main feature have been identified in HEn1 beach by EOF analysis. The southern feature, located in proximity of the river mouth, shows an opposite trend in comparison to the two features located at north. This could be interpreted as due to net exchange of material between the different beach sectors. The material includes both sediment that Posidonia litter as shown by the analysis of variability of the two grids (banquettes and sediment grids).

In HEn2 beach a wide morphological feature, located in the area of deposition of banquettes, shows and opposite trend of morphological variability in comparison to the northern sector of the beach were banquettes are absent. In this case the morphological changes involve exchange of sediments between the two beach sectors. The presence of banquettes only in the southern sector is probably related to the complex submerged morphology driven by the presence of rocky reefs.

In contrast the morphological variability of the low energy beach can be related to two different processes: (i) the interference of the jetty on the longshore current and (ii) the banquettes deposition. The former process explains the variability of the sediment-banquettes interface surface (sediment grid), the latter explains the variability of the banquettes grid. The two processes do not show any relationship. Banquettes deposition does not involve significant modifications of the underlying morphology.

Banquettes deposition has different roles in influencing geomorphology in high and low energy beaches. In high energy beaches banquettes concurs with sediment to the morphological changes driven by beach dynamics process, in low energy beaches banquettes are deposited over a general invariant surface and vegetation litter deposition itself concur to the beach geomorphology (Jackson et al. 2002).

The analysis of beach profiles allows to better understand the relationship between banquettes deposition and backshore morphological features.

In figure 4.11 are reported the mean beach profiles and relative standard deviations extracted from representative beach sectors where greater accumulation of banquettes and morphological variability occur. The location of beach profiles is reported in figure 4.4. Beach profiles have been extracted from banquettes and sediment grids.

In high energy beaches banquettes contributes to the berm formation while in the low energy beach banquettes are distributed as an more uniform layer on the sediment substrate. The profile of standard deviation shows that in high energy beaches the maximum variability of banquettes and sediment grid is located in correspondence of the berm/foreshore sectors. In high energy beaches banquettes contribute to shoreline progradation. In the low energy beach the maximum values of standard deviation of banquettes grid is located in proximity of the foreshore while the standard deviation profile of sediment grid is lower and quite constant.

Based on this finding some consideration on the impact of banquettes removal on beach geomorphology can be carried out. Banquettes removal from high energy beaches could significantly alter the processes which controls beach geomorphology allowing to the removal of material from the berm. Consequently removal could interferes with the exchanges of sediment between the berm and the bars (Masselink and Hughes, 2003) and lead to shoreline retreat. In the low energy beach banquettes removal does not directly influence the sediment dynamics of the beach, consequently those beach are probably less sensitive to this impact.

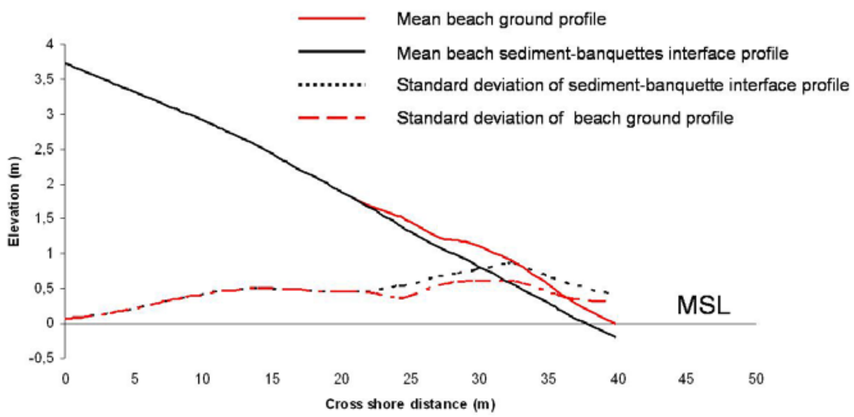

Figure 4.11a: mean beach profiles and standard deviation profile for sediment and banquettes grids in HEn1 beach

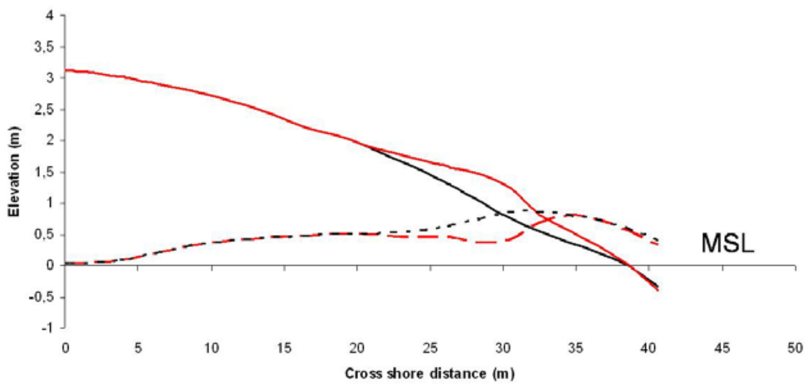

Figure 4.11b: mean beach profiles and standard deviation profile for sediment and banquettes grids in HEn2 beach

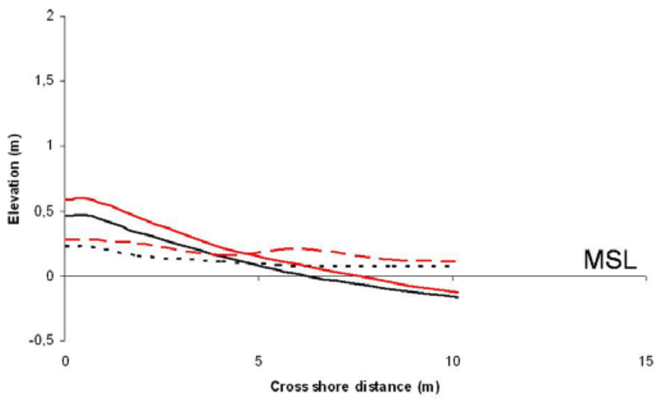

Figure 4.11c: mean beach profiles and standard deviation profile for sediment and banquettes grids in LEn beach

4.6 Conclusions

- In high energy beaches the deposition dynamics of banquettes is strictly related to the beach dynamics. Banquettes concur with sediments to the morphological changes driven by beach dynamics process and contribute to the berm formation.
- In the low energy beach banquettes are deposited as a layer over a generally invariant sedimentary substrate and vegetation litter deposits itself concur to the beach geomorphology.
- Banquettes removal from high energy beaches could significantly alter the processes which controls beach geomorphology, while the low energy beach is probably less sensitive to this kind of impact.

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CHAPTER 5

Posidonia Oceanica 'banquettes' removal: Environmental Impact and Management implications

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Abstract

The removal of beach-cast Posidonia oceanica seagrass litter, called ‘banquettes’, was analyzed on the island of Sardinia (western Mediterranean) in order to quantify this practice on a broad scale, to evaluate the potential impacts on the beach geomorphology and the ecological implications for coastal ecosystems. ‘Banquettes’ removal resulted to be a widespread practice applied on 44 beaches (out of 116), along 114 km of shoreline out of the 289 km analyzed; in the year 2004 the total amount removed was 106,180 m^3, mainly in low energy beaches. Meadow leaf production was assessed in 5 localities which collectively account for about 70% of P. oceanica removed from Sardinian beaches; the loss of biomass due to the removal varied between 1.8 and 14.9% of meadow production. The main consequences of leaf material removal are the loss of sediment and the permanent depletion of biogenic elements from the shore. Management measures are suggested in order to minimize the possible effects on the dynamics of shoreline and the growth in front of the meadows.

Key-words: *Posidonia oceanica, banquettes, Sardinia, beach cleaning, leaf production.*

5.1 Introduction

Seagrass meadows represent extremely productive systems in coastal areas all over the world (Buia *et al*., 2000; Duarte, 2002). Most of the production is due to the aboveground compartment (i.e. leaves) (Romero *et al*., 1992; Pergent-Martini *et al*., 1994) of which only a small amount is consumed *in situ*; most of the leaf material becomes litter, that can be decomposed within the meadow, exported to other ecosystems or which accumulates on adjacent shorelines (Walker *et al*., 2001).

Posidonia oceanica (L.) Delile (Potamogetonaceae) loses leaves in autumn (Romero *et al*., 1992; Chessa *et al*., 2000) and beach-cast litter can be found in coastal areas where extensive seagrass meadows occur, forming deposits known as 'banquettes' up to 2 m in height (Boudouresque and Meinesz, 1982). Banquettes are often removed because they are believed to reduce the touristic value of beaches (Mateo *et al*., 2003; Duarte, 2004).

Banquettes may affect beach profile trapping high amounts of sediment and reducing its movement (Chessa *et al*., 2000); as a consequence banquettes removal could influence the beach sediment budget. On the other hand their removal could play an important role in the nutrient budget of the meadows, as the leaf litter is the main source of biogenic elements (Romero *et al*., 1992).

In this work, removal of *P. oceanica* banquettes and related management practices (i.e., frequency and removal techniques) were quantified at a regional scale on the island of Sardinia (Italy, Western Mediterranean). The relationship between banquettes removal and beach characteristics, as well as the amount of sediment subtracted from beaches during the cleaning operations, were estimated in order to evaluate the impact of banquettes removal on the beach sediment budget. Moreover, the mass balance between meadow leaf production and the amount of banquettes removed were evaluated for five localities which together accounted for about 70% of the leaf material removed from Sardinian beaches. The nutrient export represented by the removal of banquettes was assessed in order to evaluate the permanent loss of carbon, nitrogen and phosphorous for *P. oceanica* meadows and coastal ecosystems.

5.2 Materials and methods

Sardinia region has a coastal length of 1,896 km (Figure 5.1) of which 289 km, corresponding to 116 beaches, were investigated. Data on deposition and removal of banquettes were collected from the technical services departments of coastal municipalities by means of a questionnaire.

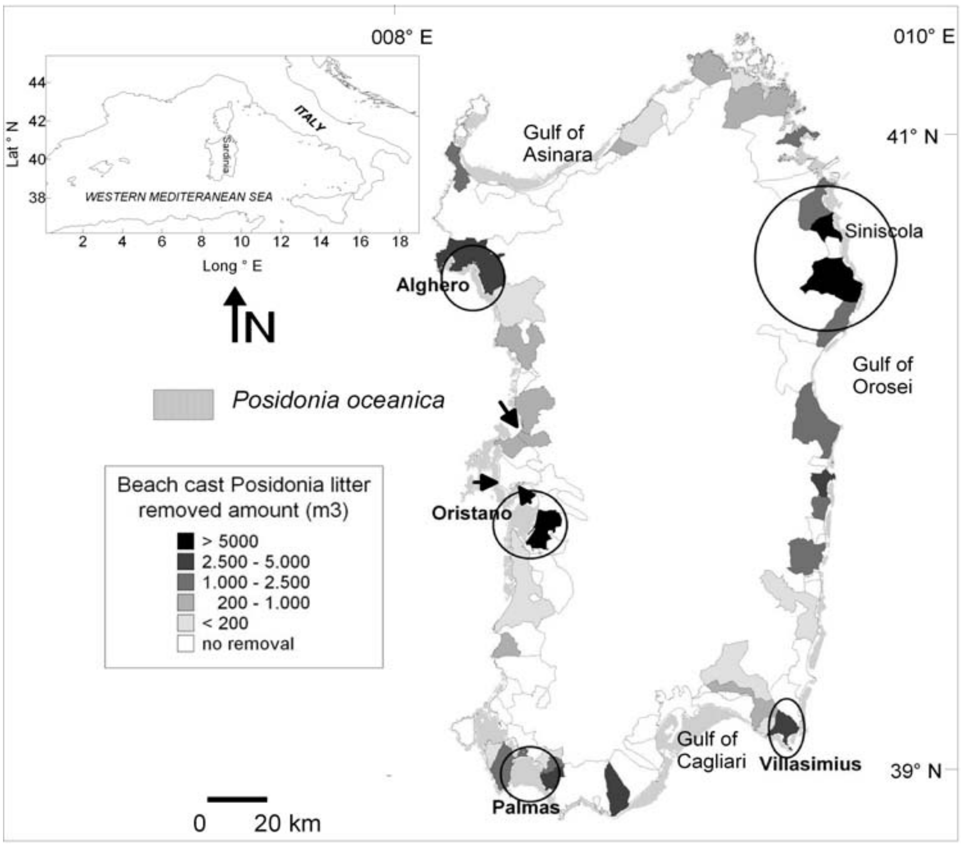

Figure 5.1. Map of Sardinia region showing the amounts of beach-cast *Posidonia* litter removed. Arrows indicate the three experimental sites used to estimate the sediment content in 'banquettes'; circles indicate the five locations where meadow primary production was assessed .

The amount of removed sediment trapped in the banquettes was estimated in three localities on the western Sardinian coast. Banquettes samples were collected using a box (20 x 20 x 20 cm) and the sediment was separated from the leaves by wet sieving and then weighed.

Multivariate Factor Analysis (Dal Cin and Simeoni, 1996) was applied on morphodynamic variables (Atzeni *et al*., 2004) and banquettes removal data from 30 beaches (Table 5.1).

Meadow shoot density was calculated for 15 sites in the neighbourhood of the five selected localities (Figure 5.1) and 30 orthotropic rhizomes were sampled for lepidochronological analysis. Primary leaf production per m^2 was calculated according to Pergent-Martini *et al*. (1994). Meadow production was calculated multiplying leaf production and meadow surface area obtained in the framework of the "Mappatura delle prateria di *Posidonia oceanica* lungo le coste della Sardegna e delle piccole isole circostanti" (Buia, unpbl. Data).

5.3 Results

In 2004 banquettes were cleared from 44 of the 116 beaches studied and the total removed material amounted to 106,180 m^3. The frequency of removal was generally once a year (26 beaches out of 44); 8 beaches were cleared twice and 10 three or more times a year. The removal operations were generally carried out using heavy machinery such as bulldozers and excavators (25 beaches). Removal was carried out by hand on 6 beaches and by specialised beach-cleaning machines on 13 beaches.

The sediment content in the banquettes samples showed a normal distribution with a mean value of 68.1 kg m^{-3} (C.I. ± 95% 50.6 – 85.7 kg m^{-3}; n=50). From the Factor Analysis, three factors explained 71.9% of total variance (Table 1). Factor 1 (38.8%) grouped energy variables with those related to banquettes removal, highlighting that low energy beaches had a higher amount of removed banquettes for unit beach length. Factor 2 (16.5%) grouped variables related to beach morphology and Factor 3 (16.6%) grouped variables related to sediment texture.

Table 5.1. Score coefficient and explained variance resulting from Factor Analysis of beach parameters.

Variable		Factor 1	Factor 2	Factor 3
Energy variables				
$\mathbf{E_F}$ – Mean energy flux	GN m m^{-1}	**0.86**	0.19	0.02
$\mathbf{E_L}$ – Longshore Energy (from left direction)	W m^{-1}	**0.81**	0.17	0.05
$\mathbf{E_R}$ – Longshore Energy (from right direction)	W m^{-1}	**0.66**	0.31	-0.25
$\mathbf{E_N}$ – Net energy flux	W m^{-1}	**0.77**	0.13	0.14
Beach morphology variables				
$\mathbf{B_L}$ – Beach lengths	m	0.22	-0.04	**0.81**
$\mathbf{B_W}$ – Backshore width	m	0.01	-0.01	**0.87**
Sediment texture variables				
$\mathbf{S_E}$ – Emerged beach sediment grain size	mm	0.04	**0.84**	-0.16
$\mathbf{S_S}$ – Submerged beach sediment grains size	mm	0.15	**0.86**	0.12
'Banquettes' removal variables				
$\mathbf{R_V}$ – Removed volume per beach length unit	m^3 m^{-1}	**-0.83**	0.13	-0.18
$\mathbf{R_S}$ – Average decrease of emerged beach elevation	mm	**-0.83**	0.11	-0.30
Explained variance (Total 71.9%)		**38.8%**	**16.5%**	**16.6%**

Leaf production ranged from 226.1 g DW m^{-2} $year^{-1}$ in the Gulf of Palmas to 528.0 g DW m^{-2} $year^{-1}$ at Villasimius with values comparable to those recorded for other Mediterranean areas (Pergent-Martini *et al.*, 1994). Beach and meadow features, litter removed and carbon and nutrient losses for the 5 locations studied are given in Table 2.

5.4 Conclusion

Banquettes were removed from 40% of the analyzed beaches, indicating that this practice is common along the coast of Sardinia.

The findings of this study allow a preliminary evaluation of the environmental impact of 'banquettes' removal on coastal geomorphology. Banquettes removal is mainly carried out on low energy beaches. Banquettes clearing and the concurrent sediment removal may lead to substantial changes in beach morphology, including possible shore erosion following storm events. Post-storm beach recovery on low energy beaches occurs at a slow rate (Jackson *et al.*, 2002) and consequently the impact of banquettes removal before a storm event could have an effect on beach morphology for prolonged period.

In addition, banquettes represent a temporary sink of biogenic elements for the seagrass ecosystems (Mateo *et al*., 2003), and their removal causes a permanent loss of C, N and P. Nutrient depletion was extremely variable among five locations studied. The highest N and P losses (respectively 2.3-5.4% and 0.6-1.2% of the annual requirement of the plant as estimated by Romero *et al*., 1992; Mateo and Romero, 1997; Gacia *et al*., 2002) was found at Villasimius. The relevance of this nutrient loss should be investigated further.
In conclusion, the removal of banquettes during winter and spring should be discouraged to avoid shore erosion after storm events. Removal during summer period should be subject to an Environmental Impact Assessment procedure, to minimize the impact of removal (i.e. avoiding heavy machineries) and to suggest possible mitigation measures.

Table 5.2. Beach and meadow features in the studied localities.

Location		**Alghero**	**Oristano**	**Palmas**	**Siniscola**	**Villasimius**
Covered beach length	km	2.0	0.9	6.0	8.6	0.7
Mean meadow density	shoots m^{-2}	302.1	311.3	241.0	314.6	465.4
Meadow surface	km^2	10.3	85.1	75.5	59.0	4.3
Annual leaf production	g DW $m^{-2}y^{-1}$	253.9	325.4	226.1	231.7	528.0
	tons DW $meadow^{-1}y^{-1}$	2605.1	27701.5	17077.2	13671.1	2281.1
Litter removed	tons DW	171.9	586.1	304.8	2031.9	156.3
Loss of biomass	% of leaf production	6.6	2.1	1.8	14.9	6.9
Loss of biogenic elements	kg DW C $km^{-1}y^{-1}$	33612.1	254637.3	19861.7	92380.0	94019.9
	kg DW N $km^{-1}y^{-1}$	679.1	5144.8	401.3	1866.5	1899.6
	kg DW P $km^{-1}y^{-1}$	18.1	136.8	10.7	49.6	50.5

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CHAPTER 6

General remarks

6.1 General Remarks

This study allows to highlight the following remarks:

- **Posidonia banquettes removal is a diffused practice, the amounts of removed material are higher on low energy beaches.**

A total volume of 106,180 $m^3$of banquettes have been removed from Sardinian beaches during the period of study. Removal operation involve 114 km of beach overall the Sardinian coast.

- **Removal operations of banquettes were conducted mainly with heavy machine (i.e. bulldozer) and in same case removal operations were carried our more than one time per year.**

About the 80% of total material removed from the beaches was removed with heavy machine, in four beaches frequency of removal operation is four per year.

- **Banquettes deposition occurs during the final phases of a storm event, when wave energy decreases.**

Deposition of litter and sediments starting from the swash uprush line when the wave energy begin to decrease.

- **The development of wider and thicker banquettes in high energy beaches in comparison with the low energy beach is due to the wider swash zone.**

The landward limit of banquettes marks the maximum wave run-up and banquettes deposition occurs seaward following the run-up decrease.

- **Sediment concentration in banquettes is independent from the beach energy. Sediment concentration is higher in the backshore sector of banquettes in comparison to the foreshore sector of banquettes.**

Landward heavier material are deposited leading to higher sediment concentration and rhizome biomass in the backshore in comparison with the foreshore, rhizome uprooting require heavy storm condition, consequently they were absent in low energy beach.

- **Banquettes deposition has different roles in influencing geomorphology in high and low energy beaches**

In high energy beaches banquettes concurs with sediment to the morphological changes driven by beach dynamics process, in low energy beaches banquettes are deposited over a general invariant surface

- **Banquettes removal operations can causes the subtraction of hundreds of cubic meter of sediment and can substantially unbalance beach sedimentary budget.**

Considering the mean banquettes volume and the mean sediment concentration obtained in this study we can estimate the total volume of sediment trapped in banquettes which ranged from 6 to 79 m^3. Based on this data the removal of 1000 m^3 of banquettes involves the subtraction of 19-44 m^3 of sediments.

- **Banquettes removal from high energy beaches could significantly alter the processes which controls beach geomorphology. While the low energy beach is probably less sensitive to this kind of impact.**

In high energy beaches banquettes contributes to the berm formation while in the low energy beach banquettes are distributed as a layer on the sediment substrate. However banquettes contribute to shoreline progradation

- **Banquettes removal causes a permanent loss of C, N and P.**

The loss biogenic elements following banquettes removal is generally low. The loss of biomass varied between 1.8 and 14.9% of meadow production, while the loss nutrient (N and P) was < 6%.

Following this remarks some management issue deriving from the findings of this work can be used as guidelines for minimize the impact of banquettes removal on costal geomorphology and coastal ecosystem and following the disposal of removed material (Table 6.1).

Table 6.1 : Impact on coastal area, possible mitigation measure and further needed studies

	Impact	Results from This study	Possible impact mitigation	Further Needed studies
Coastal Geomorphology	Beach erosion due to changes of beach morpho-dynamic behavior	In high energy beaches banquettes concurs with sediment to the morphological changes driven by beach dynamics process and contribute to the berm formation. In the low energy beach banquettes are deposited as an more uniform layer over a generally invariant sedimentary substrate.	Not remove in winter and spring (when storm event may occurs). Not remove Posidonia leaves banquettes from cusps and berms.	Interactions between banquettes and beach morphodynamic overall the emerged and submerged beach.
	Beach erosion due to subtraction of sediment	Sediment concentration in banquettes is independent from the beach energy. Sediment concentration was higher in the backshore sector of banquettes in comparison of the foreshore sector. Banquettes removal can substantially unbalance beach sedimentary budget.	Adopt removal systems which minimize sediment subtraction (handy removal); leave 10 cm of leaves on the beach; Use of grid systems;	Relationships between sediment grain size and banquettes sediment concentration in banquettes
Coastal Ecosystems	Subtraction of biomass (and related nutrients) from the coastal ecosystems	The loss of biomass varied between 1.8 and 14.9% of meadow production, the loss nutrient (N and P) was < 5%.	To subtract low amounts of biomass and related nutrients in relationship to meadows production	Role of banquettes biomass in the trophic web of coastal ecosystems and the potential loss of habitat
Disposal of removed material	Production of waste. Soil pollution (i.e. heavy metal)	80% of removed material disposed in non authorized plant. Possible heavy metal pollution.	Do not export polluted banquettes outside the beach. Recycle the removed material.	Recycling technologies for *Posidonia oceanica* leaf litter.

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